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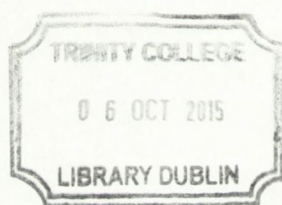
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**A SOCIO - TECHNICAL EVALUATION OF THE EFFECTIVENESS
OF SOCIAL HOUSING ENERGY EFFICIENT UPGRADING IN
IRELAND**

**A thesis submitted for the Degree of Doctor of Philosophy
to the University of Dublin, Trinity College.**

Derek Sinnott

Supervisor: Prof Mark Dyer



Thesis

10875

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Summary

This dissertation evaluates the results from a multi-level multidisciplinary study on the effect of energy efficient upgrading on social housing. The National Energy Efficiency Action Plan aims to deliver a 20% national energy saving in accordance with EU 2020 targets. The Irish government is investing heavily in a number of what may be described as 'shallow retrofit' schemes in an attempt to significantly reduce domestic energy consumption and associated carbon dioxide emissions and meet the 2020 targets. Funding is administered through a number of schemes including the 'Social Housing Investment Programme'.

However, there is a dearth of empirical data to demonstrate the actual benefit of energy efficient retrofitting in the residential sector across Europe. Much of the research to date has focused on the technical aspect of energy use. Due to the complexity of the interdependence of a number of variables including building fabric, climate conditions and occupant behaviour there is a great deal of difficulty in accurately predicting actual operational building energy performance to a reasonable degree of accuracy.

The primary aims of the study is to establish the actual energy savings achieved through energy efficiency upgrading and to understand the drivers of energy use in the domestic sector, combining quantifiable data with perceptual information. The main study focused on assessing the effect of upgrading on energy performance on nine dwellings in Kilkenny. The study was augmented by number of additional studies. This included assessing energy performance and airtightness of dwellings across a range of ages in Waterford. The effect of the energy efficiency upgrades on airtightness and associated heat loss was completed as part of in the Kilkenny study.

The research adopted a three phase multidisciplinary approach in order to triangulate findings. Phase one involved the collection of survey data through BER's, airtightness testing and as well as from interviews. The second phase involved the design and installation of an energy monitoring system to record actual energy consumption and environmental parameters pre- and post- the upgrading. The third phase was an in-depth qualitative study which examined the under researched area of the influence of occupant behaviour on energy use. This part of the methodology was used to gain an understanding of the principles and perspectives of *how* and *why* occupant behaviour affects energy use.

The findings of the research indicate that substantial energy savings can be achieved by energy efficient upgrading. However, the overall consumption patterns and energy savings varied considerably between households. The quantitative results yielded no insight as to the reason for the different usage patterns. The interviews revealed that occupants had different perceptions of

their energy use with varying levels of awareness about their consumption and how to reduce their energy bills. A co-benefit of the upgrading is that there was a considerable increase in dwelling airtightness. This has the benefit of additional energy savings which are not satisfactorily accounted for in the Dwelling Energy Assessment Procedure methodology. The benefits go beyond just energy savings and help to improve the overall living standards of the occupants. Whilst the occupants were generally happy with the upgrading, they did complain about the additional design ventilation installed saying that they were noisy, annoying and draughty. Consideration needs to be given to future upgrading programmes to counteract this limitation.

Considering the Triple Bottom Line approach adopted, the upgrading resulted in a reduction of energy consumption, an increase in comfort for the occupants, but with a considerable payback period this represents a poor return on investment. Finally, this thesis proposes a number of measures to improve future outcomes of energy efficiency upgrading programmes.

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This work is dedicated to the memory of my late mother, Breda Sinnott.

"All that I am or ever hope to be, I owe to my angel mother." —Abraham Lincoln

She gave up so much and often went without to ensure I received the best education possible.

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"Any fool can know. The point is to understand."

Albert Einstein

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Abbreviations

ACH	Air Changes per Hour
BER	Building Energy Rating
CDD	Cooling Degree Days
CF	Conversion Factor
CO ₂	Carbon Dioxide
DC	Data Concentrator
DCV	Demand Control Ventilation
DEAP	Dwelling Energy Assessment Procedure
EE	Energy Efficient
EPBD	Energy Performance of Buildings
EU	European Union
HDD	Heating Degree Day
KCC	Kilkenny County Council
LA	Local Authorities
LBL	Lawrence Berkeley Laboratory
M&T	Monitoring and Targeting
M&V	Measurement and Verification
MV	Mechanical Ventilation
MHVR	Mechanical Heat Ventilation Recovery
NPI	Normalisation of Performance Indicators
OMR	Optical Meter Readers
Pa	Pascals
PCB	Printed Circuit Board
PHPP	Passive House Planning Package
SAP	Standard Assessment Procedure

Abbreviations

SHIP	Social Housing Investment Programme
SWH	Space and Water Heating
TBL	Triple Bottom Line
TGD	Technical Guidance Document
WCC	Waterford City Council

Units

Pa	Pascals
kW	kilowatt

Chapter 1

The terms of energy efficient retrofit and upgrade are often used interchangeably but it is important to differentiate between both. The National Refurbishment Centre (NRC) (NRC, 2012 p. 8) define:

- 1) Upgrading refurbishment as referring to 'multiple energy-efficiency measures, applied sequentially as part of a whole building solution';
- 2) Retrofit as 'the installation of a specific measure – example installation of Solar Panel.

1 Introduction

Energy use has risen to become a central pillar of geo-political world policy in the past couple of decades. The traditional extensive and increasing usage of fossil fuels was seen to be unsustainable and energy prices and supply led to many crises. Allied to this, it became accepted that burning fossil fuels is having catastrophic effects on our environment. Al Gore, vice president of the USA under Bill Clinton, was one of the key advocates to tackling global warming on a world-wide scale. His documentary –*The Inconvenient Truth* was particularly influential in shaping public opinion. This research aims to contribute to this body of knowledge in the following ways. On the technical side, the research examines how energy efficient (EE) upgrading buildings can impact on energy usage and secondly, the research explores the under researched area of how occupant behaviour affects energy use.

Energy efficiency is widely recognised as one of the fundamental pillars of modern energy policy. In accordance with the Kyoto Protocol and subsequent EU burden-sharing, Ireland, through its National Climate Change Strategy, was obliged to limit its carbon dioxide (CO₂) emissions to 13% above 1990 levels by 2012. Emissions of CO₂ were still some 23% above 1990 levels by 2013 and governments across Europe are struggling meet these targets. In addition, Ireland's energy supply is in a particularly precarious position because it is almost entirely dependent on imported fossil fuels. Buildings account for more than 40 % of Europe's energy consumption, 64% of which is accounted for by the residential sector in Ireland (IEA-ECBCS, 2008, Howley and Holland, 2013). With such a large share of total consumption, improving the energy performance of buildings is key to achieving the EU objective of reducing energy consumption and greenhouse gas emissions by 20% by 2020.

The EU Action Plan for Energy Efficiency states the most cost-effective means of realising these savings is in the residential sector with a potential to reduce energy use by 27% (CEC, 2006). It is estimated that there are 25 billion m² of useful floor space in the EU27, Switzerland and Norway (BPIE, 2011). Non-residential buildings account for 25% of the total stock in Europe and comprise a more complex and heterogeneous sector compared to the residential sector. Social housing managed by Local Authorities and non-profit housing associations, equate to 9.7% of the total housing stock (DECLG, 2014, ICSH, 2013). This figure may be under reported as there are other households supported by rent allowance in private rented accommodation.

Requirements under Kyoto and European Union directives and legislation have driven the need to undertake energy efficiency measures in Ireland's residential sector. The National Energy Efficiency Action Plan (NEEAP), launched in May 2009, identified current and new measures to

achieve the requirements of Energy Services Directive (ESD) 2006/32, which set a 9% energy savings target by 2016. The plan also introduced further energy saving targets, of 20% nationally, and a more onerous public sector target of 33% by 2020.

Energy is used in the design, construction, operation, maintenance and disposal in a buildings life cycle. However, a study by (Ramesh *et al.*, 2010) found that the buildings embodied energy accounts for 10 – 20% of the overall lifetime energy use. The majority of energy use occurs during the operational stage of the building. This operational energy use offers the best potential to reduce energy demand even if there may be an increase in embodied energy. The Irish Government is investing up to €100 million in programmes to support efficiency upgrades in older homes in an attempt to substantially reduce carbon emissions from dwellings (DCENR, 2009). The technical effects of these upgrading measures such as increasing attic and wall insulation, improving boiler efficiencies and heating controls are well understood. However, there is a scarcity of empirical data to demonstrate the actual benefit of energy efficient retrofitting in the residential sector across Europe. This is highlighted by Meijer *et al.* (2009) who sought to assess the performance of dwellings in eight countries across Europe and found that detailed end-use data is lacking and current statistical methods of assessment are different in each country. Where empirical research has been undertaken, the evidence suggests that observed energy demands are often higher than expected (Rogan and Gallachoir, 2011, Cayre *et al.*, 2011).

The residential sector accounts for approximately 27% of all primary energy used in Ireland with the 'average' dwelling consuming approximately 20,000kWh of energy in 2011, 75% of which is non-electrical consumption (Dennehy and Howley, 2013). While climate corrected energy use in the residential sector in Ireland has reduced significantly, overall the housing stock has been identified as being one of the least energy efficient in the EU-27 (Lapillonne *et al.*, 2012, Howley *et al.*, 2012).

Nationally Local Authorities are in the process of upgrading their older existing housing stock. Their housing policy has the twin objectives of both increasing living standards and comfort levels for occupants while simultaneously reducing energy use in the dwelling. Funding is provided by the Department for the Environment, Community and Local Government through a number of funding mechanisms including the 'Social Housing Investment Programme (SHIP)'.

The Irish government's policy to their existing social housing stock is in a state of transition, from simple supply and maintenance to one of strategically aiding Ireland's reduction of carbon emissions.

To comply with the European Directive 2002/91/EC, Ireland has adopted the Dwelling Energy Assessment Procedure (DEAP) as the official methodology for calculating the energy performance of buildings. The DEAP calculation framework, based on IS EN 13790, is adapted for Irish conditions. DEAP draws heavily on the calculation procedures and tabulated data of the UK Standard Assessment Procedure (SAP), itself based on the BRE Domestic Energy Model (BREDEM) (BRE, 2009). DEAP calculates a monthly energy balance, but does not take account of geographical location and assumes standard occupancy, duration of heating and usage of appliances (SEAI, 2012a). Thus, the results are independent of household size and energy use patterns offering only an estimate of real energy use of the building. In reality, such procedures are over simplified for the accurate evaluation of energy policies and the undertaking of detailed assessments, such as life cycle analysis. From a research perspective, there is a dearth of detailed utility and building environmental data, supported by extensive occupant information to demonstrate energy use patterns and actual benefit of energy efficient retrofitting in the residential sector. This necessitates the inclusion of socio-economic variables in addition to technical attributes in energy assessments to realistically evaluate energy policies.

Detailed assessment of energy consumption and energy efficient upgrading of dwellings is required to close the gap in knowledge between theoretical and actual energy use. Drawing on the lack of real life data for whole dwelling energy use patterns, a baseline of energy usage must first be established from which improvements and efficiencies can be measured.

1.1 Problem Statement

Current approaches to predict domestic sector energy use and measure the benefits of energy efficient upgrading are not evidence based, make a large number of general assumptions and lack detail.

1.2 Research Questions

Can a systematic, evidence based approach provide the knowledge and level of detail required to understanding domestic energy consumption patterns and the benefit of energy efficient upgrading?

1.3 Aim

The aims of this work are to add to the body of knowledge about actual domestic energy consumption and evaluate the benefit of energy efficient upgrading of Social Housing in Ireland using an evidence based approach. The researcher proposes to use the findings to make recommendations informing stakeholders and policy makers with the necessary data and knowledge to improve the outcomes of energy efficient upgrade schemes.

1.4 Objectives

1. To review the present body of knowledge surrounding relevant aspects of domestic energy consumption in the social residential housing sector;
2. To develop and implement a methodology to remotely monitor dwelling energy use and environmental conditions;
3. To compare real monitored data with predicted Building Energy Rating (BER) energy consumption;
4. To evaluate the effect of energy efficient upgrading using socio technical inputs taking into account the profiles of occupant characteristics and physical dwelling parameter to quantify actual energy savings;
5. To examine upgrading successes, barriers and identify the potential to improve the outcomes of energy efficient upgrading schemes and transfer national housing stock.

1.5 Contribution

Fellows and Liu (2003 p. 4) describe research as a *"voyage of discovery"* consisting careful search and investigation. Oreszczyn and Lowe (2010 p. 112) describe past research in building energy as resembling *"a cottage industry"* rather than a mature research area with *"weakness in formal structures to promote and sustain a common research culture"*. This dynamic empirical research project, undertaken over a considerable timescale, will facilitate the generation of a research culture in the area of residential energy performance in Ireland. This thesis proposes a novel mixed mode evidence-based approach to determine energy use and drivers for such use in social housing. The purpose of this research is to carefully assess and contribute to the current body of knowledge and facilitate the learning process. This work represents the most recent detailed attempt undertaken to establish a real energy use and environmental characteristics attributable to housing in Ireland.

This study aims to make a number of important contributions to this area of research, including:

- Challenging the paradigm that there is a figuratively de-facto linear relationship between technical energy efficient upgrading and energy use;
- Increasing the theoretical understanding of the complex inter-relationships between the various energy end-uses in Irish social housing, and also the relationship between energy use and occupant behaviour;
- Providing a framework for a low cost system to remotely monitor and assess real energy use and environmental parameters in domestic.

Significantly the research objectively identifies weaknesses in the current practices with respect to holistic approaches to whole building energy management and efficiency in dwellings and address how these criteria can be improved.

1.6 Challenges

There are no established and tested parameters to characterise dwelling energy consumption. It followed that the study was informed by previous research methodologies but a number of new processes and systems required development. The key to the monitoring programme was to influence occupant behaviour as little as possible; thus, the monitoring system had to be robust and report externally and remotely. There is no 'off-the-shelf' remote energy monitoring system or protocols designed for domestic sector implementation. All individual sensor components can be sourced easily but there is not an integrated one size fits all system. The timescale for development of the system was very short and needed to be installed before the start of the heating season. The study was self-funded with a zero capital or consumables budget available to carry out any monitoring. Dealing with a third party, namely the Local Authority, though very beneficial and necessary, required in-depth coordination and protracted consultations. It was critical to establish and maintain good tenant relations on a live project with expensive and delicate equipment. This meant that the selection process had to be carefully planned and multi-layered authorisation attained and adhered to. Consequently, the tenants selection process included a large amount of tenant liaison and vetting to as much as possible ensure that the monitoring would be successful.

1.7 Why Study Social Housing as a Case Study?

This study focuses on Social Housing for a number of reasons including:

- Ravetz (2008 p. 4462) states that “the life cycle of physical buildings is a function of their social and economic value”. It follows that Local Authorities (LA) have an inherent interest to maintain and improve their buildings’ quality to increase the buildings’ life cycle and also improve the quality of life for the occupants;
- NAMA are currently the largest property company in Ireland. NAMA will, in all probability, be disbanded in a few years as the development of NAMA was a forced measure when the Irish economy crashed. Discounting NAMA, combined LA’s are the largest residential building owners in the state. LA’s are partaking in national energy efficiency upgrade programmes such as the Social Housing Investment Programme and the Better Energy Communities Programme to retrofit their building stock. Successful outcomes from this research can be used to improve the outcomes of the programmes and rewarded by a national roll out;
- As expanded on later in section 2.8 the Energy Services Directive require public bodies such as Local Authorities to act as exemplars in the context of the directive;
- Social housing occupants tend to have lower incomes and are at higher risk of fuel poverty than private households. Hence there is a greater potential benefit from any energy savings and increase in comfort made;
- The housing stock tends to be more homogeneous and urban social housing tends to be clustered making data acquisition more straightforward;
- As a self-financing research project without a capital budget it was important to get funding for equipment. Kilkenny County Council (KCC) provided the budget for the project.

With two external stakeholders, the LA and occupants, it was important to develop a methodology and a research focus that is mutually beneficial and have minimal impact on their day to day lives.

1.8 Structure

- Chapter 2 is a literature review of research pertaining to dwelling building energy use, upgrading paradigms and outcomes, efficiency and energy use patterns. It identifies gaps in research knowledge and weaknesses in current practice.
- Chapter 3 describes the methodologies, techniques and validation processes used to collect the data to establish, characterise and understand household energy use

consumption of occupants in social housing. The methodology chosen was primarily quantitative and this was followed up by a qualitative study which examined how human behaviour affected energy use. The study adopted the principle of the triple bottom line of sustainability and validated the results using the triangulation approach.

- Chapter 4 describes the application of the evidence-based methodology to establish the current state of social housing stock in terms of energy performance and airtightness. The study was to establish the most appropriate mechanisms to appraise, liaise and communicate with social housing tenants. This study offered the researcher time to develop the skills and knowledge required to carry out the technical aspects of the BER's and airtightness testing.
- Chapter 5 describes the application of phase one and two of the methodology described in Chapter 3 on social housing in Kilkenny. The chapter discusses the challenges involved in design, installation and commissioning of a bespoke energy monitoring system.
- Chapter 6 outlines the development of the analytical approach taken to establish the dwellings electricity and SWH energy load profiles, taking climate variables into account. The chapter also presents the findings of the quantitative analysis and evaluates the scale of the energy savings.
- Chapter 7 evaluates the effect of energy efficient upgrading on building airtightness and correlated energy performance.
- Chapter 8 presents the results of the pre- and post- upgrading interviews which sought to explore the occupants' lifestyle patterns and attitudes and how this impacted on their energy use.

Chapter 9 summarises the combined conclusions of the individual chapters. Each of the aims and objectives are revisited and reviewed to assess if they have been achieved.

1.9 Conclusion

The success of energy efficient upgrading of social housing traditionally has been measured by technical means using quasi-steady state energy performance methodologies. Similarly, most research to date examining the outcomes of technical interventions overlook the viewpoint of the occupant out. This research develops and implements a strategy to evaluate the benefits of energy efficient upgrading with respect to energy consumption and occupant perspectives. Rather than researching *about* the occupants the researcher was keen to research *with* the occupants.

Chapter 2

2 Literature Review

2.1 Introduction

Dwelling energy consumption characterises a complex interdependence of many interrelated quasi-steady state and highly dynamic conditions, including building fabric, external climate and occupant activities. This chapter presents a comprehensive review of previous research completed in the field of energy efficient upgrading in the residential sector. The review critically appraises the findings to identify gaps in current knowledge, including the impact of occupant behaviour as part of the matrix.

2.2 Background

Overall energy use in the Irish residential sector has increased by 32% between 1990 and 2006 but there has also been an observed Odyssee aggregate energy efficiency index (ODEX) decrease from 1997 to 2007 of 13% (SEI, 2009a, SEI, 2008b). This indicates that energy efficiency improvements have occurred. However, behavioural changes, such as increased use of space heating have negated any benefits. Like other developed countries, where lifestyle expectations are high, Ireland has a high energy usage rate relative to world averages. The total primary and final energy requirement for the country was 16379ktoe and 13600ktoe respectively giving an average annual primary energy requirement per capita of 44927kWh (1ktoe = 11.63×10^6 kWh based on the 2008 Energy Balance for Ireland (SEI, 2009c). To give a conceptual equivalent, this is equal to having 128 40W bulbs illuminated 24 hours a day, 7 days a week. The resulting carbon dioxide (CO₂) emissions equate to approximately 48 metric tonnes.

A report by SEI (2008b) showed that Ireland's residential sector is directly responsible for approximately 24% of all energy use in Ireland. Based on an Irish average 2.8 person per household (CSO, 2007), the average household final energy consumption in 2006 was 25,899kWh energy, emitting approximately 8.1 tonnes of CO₂, 59% of which was from direct fuel usage. These figures are broadly in line with the UK, while slightly higher than that in the US where 27.5% and 20.9% respectively of final energy consumption is used in the residential sector (DECC, 2009b, USDoE, 2009). These figures demonstrate the importance of building energy research as a key to achieving energy and CO₂ savings targets.

Buildings account for more than 40 % of Europe's energy use, residential buildings in Ireland accounting for 25.2% of Ireland's primary energy demand and 25.7% of primary energy related carbon dioxide (CO₂) (SEI, 2009b, IEA-ECBCS, 2008). It is postulated that through upgrading the

current building stock, carbon dioxide emissions can be reduced by up to 50% (Pellegrini-Masini *et al.*, 2010). However, there are a large number of variables that make this ascertain uncertain with studies showing only marginal improvements in energy emission through traditional upgrading works. It is clear that a reduction in building energy use and concurrent CO₂ emissions is an important component to achieving both national and international targets and directives. The Energy Services Directive (2006/32/EC) sets demanding energy efficiency targets for all EU states for 2016. Ireland has responded with the publication of a National Energy Efficiency Action Plan (NEEAP) 2009 - 2020, which sets out a path to achieve these energy savings.

2.3 Energy Performance of Buildings Directive

Following on from the Kyoto protocol, which established legally binding commitments for the reduction of four greenhouse gases (carbon dioxide, methane, nitrous oxide, sulphur hexafluoride) the EU identified carbon dioxide (CO₂) as the most significant greenhouse gas. Almost half of CO₂ emissions were derived from energy use in buildings, at that time. Council Directive 93/73/EEC of the 13th September 1993 required limitation of CO₂ emissions by improving energy efficiency, requiring member states to develop methods and systems for energy efficiency in the building sector. The directive was adopted by European Parliament and the Council on the 16th December 2002 as the Directive 2002/91/EC on the Energy Performance of Buildings (EPBD) and was published in the Official Journal OJ L 1 on the 4th January 2003. This legislation was transposed into all member states' legislation and was adopted into Irish Law by 4th January 2006.

Directive 2010/31/EU the recast Energy Performance of Buildings Directive, approved on 19th May 2010 significantly increases energy efficiency target levels in EU buildings. The directive sets out targets that all new buildings must be designed and constructed as “*nearly zero energy*” buildings by December 2020¹. Article 1 of the Directive, relating to both residential and tertiary (commercial and public) buildings, states the objectives of the Directive as to “*promote the improvement of the energy performance of buildings within the Union, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness*” (European Parliament, 2010 p. 153/17).

In the context of existing buildings, the directive sets a number of requirements (European Parliament, 2010):

- Article 3 requires member States to adopt a common general framework and develop a methodology for calculating the energy performance of buildings. The framework as set

¹ Public Authority buildings must be designed and constructed as *nearly zero energy* by December 2018

out in Annex I specifies that the methodology should include at least the following aspects (European Parliament, 2010 p. 153/29):-

Thermal characteristics of the building:

- Airtightness;
- Heating installation and hot water supply;
- Insulation characteristics of heating installation and hot water supply;
- Air-conditioning installation;
- Ventilation;
- Built-in lighting installation (mainly the non-residential sector);
- Position and orientation of buildings, including outdoor climate;
- Passive solar systems and solar protection;
- Natural ventilation;
- Indoor climatic conditions, including the designed indoor climate.

The methodology where possible shall in its calculation incorporate positive influence of the following aspects (European Parliament, 2010 p. 153/29):-

- Active solar systems and other heating and electricity systems based on;
- Renewable energy sources;
- Electricity produced by combined heat and power (CHP);
- District or block heating and cooling systems;
- Natural lighting.

In response the Irish Government adopted the Dwelling Energy Assessment Procedure (DEAP) as its National Methodology. This methodology is explored in detail in Section 2.4;

- Article 4 states that Member States shall adopt cost-optimal minimum energy performance standards; however,
- For existing buildings Article 7 requires minimum energy performance requirements to be set *“when buildings undergo major renovation”*. Where major renovation means the total cost of the renovation exceeds *“25 % of the value of the building”* or more than *“25 % of the surface of the building envelope undergoes renovation”* (p. 153/18).

Hence, there is no specific target set for the vast majority of domestic energy efficient upgrading projects. This void requires the development of policy and mechanisms to transform refurbished buildings into ‘very low energy’ buildings.

2.4 Building Energy Performance Methodologies

There are a large number of rating methodologies which can be used to demonstrate anthropogenic environmental impact. These range from individual carbon foot-printing to complex methodologies for buildings, communities and cities including life cycle analysis. The energy efficiency of a building can be established in many ways, with varying degrees of calculation method and complexity. There must be an integrated approach used when assessing energy efficiency. The methodology can be used as part of the design process and as a means of rating tool once the building is complete. The methodology to be used must also be in keeping with the provisions of the Energy Performance of Buildings Directive (EPBD). Methodologies can range from complex fully dynamic to relatively simple quasi-steady state procedures. The variety of methodologies, by their nature, leads to varying results not only between the steady state and dynamic procedures but also within each of the procedure types. The more simple procedures generally average variables over a monthly, quarterly or annual basis, whereas more complex methods average variables at far more regular intervals example half hour intervals.

A joint working group was established in 2003 to plan and direct the implementation of the EPBD in Ireland. The working group produced an Action Plan setting out a number of the key standards are essentially framework and guidance documents, requiring work at national level to convert the standards into practical operating procedures (EPBD Working Group, 2006 p 23). The EPBD working group commissioned the development of a national methodology for the calculation of energy performance of new domestic buildings based on the CEN standards in particular prEN 13790 2005, Thermal performance of buildings – Calculation of energy use for space heating.

Ireland has adopted the Dwelling Energy Assessment Procedure (DEAP) as the official methodology for calculating the energy performance of buildings in compliance with the European Directive 2002/91/EC. The DEAP calculation framework, based on IS EN 13790, is adapted for Irish conditions. DEAP draws heavily on the calculation procedures and tabulated data of the UK Standard Assessment Procedure (SAP), itself based on the BRE Domestic Energy Model (BREDEM) (BRE, 2009). DEAP calculates a monthly energy balance, but does not take account of geographical location and assumes standard occupancy, duration of heating and usage of appliances (SEI, 2008a). Thus, the results are independent of household size and energy use patterns offering only an estimate of real energy use of the building. In reality, such procedures are over simplified for the accurate evaluation of energy policies and the undertaking of detailed assessments, such as life cycle analysis.

2.5 Energy Use in the Residential Sector

Wright (2008 p. 4544) states that energy use within dwellings is a *“complex interaction between built form, location, energy-using equipment, occupants and the affordability of fuel”*. Therefore, energy use in buildings can be categorised into seven general sections:

1. Climate;
2. Building fabric and envelope;
3. Building services and systems;
4. Building operation and maintenance;
5. Occupant behaviour and activities;
6. Indoor Environmental Quality;
7. Economic and social effects.

It follows that several factors need to be considered to understand whole building energy consumption. Presently, this is a problem as there is no developed methodology to carry out such work. This has led to a research emphasis on the first three factors. In the context of measuring energy efficiency, more than ten years ago Clinch and Healy (2001 p. 123) highlighted the problem *“that a perfect methodology for evaluating large-scale energy-efficiency programmes is not yet available”* and that *“assumptions must be made about household behaviour (e.g. how will individuals react once energy-efficiency measures have been installed in their houses, i.e. it is necessary to predict the combination of comfort and savings on energy bills that will be chosen)”* and *“estimation of comfort benefits is less than ideal”*. Their statements remain as valid today as when they were written.

There have been an increasing number of studies seeking to express the relationship between a household's energy consumption and the buildings fabric, construction and occupancy rate. These studies typically only assess a small number of variables (Jokisalo *et al.*, 2009, Toman *et al.*, 2009), with little discussion about which has the most influence on energy consumption. A number have studied the relationship between household energy use and carbon emissions (Kenny and Gray, 2009, Lowe, 2007, Shorrocks *et al.*, 2005). Some investigate the relationship between the buildings' characteristics and indoor environment (Bluyssen, 2010, Yohanis and Mondol, 2010).

Many of these studies rely on models based on notional buildings to make assertions about the effect of policy implementation on energy efficiency (Uihlein and Eder, 2010, González *et al.*, 2011) and assess various energy performance parameters relating to whole buildings energy use

and related cost of upgrading (Pellegrini-Masini *et al.*, 2010, Hamilton *et al.*, 2011, Olesen and de Carli, 2011). Oreszczyn and Lowe (2010) highlight the fact that energy performance in the domestic sector is highly complex and in many cases poorly understood. This is as a result of a dearth in real data on the actual housing performance, which is leading to a “*progressive widening of the gap between theory and practice*” (p. 110). This supports the findings of Wingfield *et al.* (2008) and the editorial by Lomas (2010) who emphasise the value of detailed testing and monitoring across an number of research disciplines to understand building performance. Recent studies which seek to develop the long term detailed understanding of energy performance, life cycle effects and costing on building energy efficiency and increased thermal efficiency identified the lack of empirical research and real data as an impediment to making useful conclusions and adding to policy debate (Morrissey and Horne, 2011, Rogan and Gallachoir, 2011).

Space heating accounts for the single largest proportion of energy use in dwellings in Europe, as shown in Figure 1.

One of few empirical studies by Issacs *et al.*, (2006) also found that space heating accounts for the largest proportion of residential energy used in New Zealand. The Household Energy End-use Project (HEEP) report based on the HEEP Database which holds energy, temperature, social and physical data on 400 randomly selected houses which have been monitored from 1997 to 2005. Approximately 300 of the 400 houses were monitored over an 11 month period between 2002 and 2005. Results showed space heating accounts for 34%, hot water 29%, appliances 13%, refrigeration 10%, lighting 8% and cooking 6%.

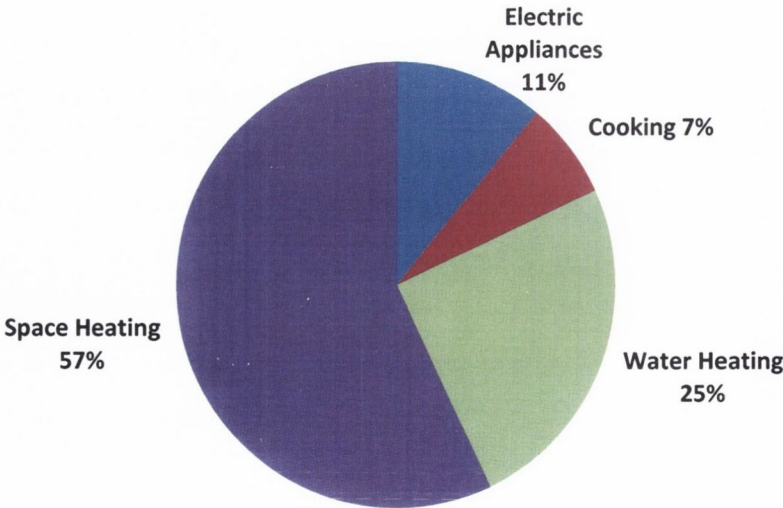


Figure 1 Energy consumption in the residential sector in European Union countries: breakdown in end-use (EuroACE, 2004)

Utleay and Shorrock (2008) using the BREHOMES model estimate that in the UK across all house types space heating accounts for around 58% and hot water 25% of the total energy consumption. There is a variation in the results of energy use in the two countries which may have resulted as a difference of methodology or directly as a result of climate variation. This is often expressed in terms of degree days for heating (HDD), which is explained in detail in Section 2.14. On average, New Zealand has approximately 50% of degree heating days of the UK (Degree Days.net, 2009). This may explain the proportional difference in space heating consumption. With Ireland having a similar climate and comparable house types to the UK and given the scale of energy use for space heating both in the UK and New Zealand there is significant scope not only to enhance thermal comfort levels but also to reduce energy consumption in the residential sector by reducing the heating load through improved thermal performance of the building fabric. The EIB (2013) believes that the most cost effective way to meet the EU's energy targets is by investing in energy efficiency programmes.

2.6 Indoor Environment

The constitution of the World Health Organisation defines good health as *"a state of complete physical, mental and social well-being, not merely the absence of disease and infirmity"* (WHO, 1946 p. 2). Therefore, the indoor environment of a dwelling should exist to promote health, not merely to avoid illness. Good health may be enhanced by providing living and working conditions that are 'comfortable'. Comfort is a term that is inherently subjective and therefore difficult to define. Milne and Boardman (2000 p. 413) state that the sensitivity of humans to *"thermal comfort combines physiological and psychological effects"*. One attribute of comfort is optimal thermal comfort, which Gut and Ackerknecht (1993), define as the situation in which the least extra effort is required to maintain the human body's thermal balance. This comfort zone varies greatly between individuals and depends on clothing worn, physical activity, metabolic heat production, and age and health condition. Geographical location also plays a role because of habit and the acclimatisation capacity of individuals.

Abnormally high vertical temperature differences between head and ankles can result in discomfort; a temperature difference of more than 3 °C should be avoided (THERMIE, 1994). Increases in lifestyle and comfort demands have meant that the mean internal dwelling temperature is estimated to have risen from about 13 – 19 °C between 1970 and 2001. Personal comfort has clearly taken priority over carbon savings (Lowe, 2007).

Four main factors, in addition to many other psychological and physiological factors, have been recognised as affecting the comfort zone (CIBSE, 2006a):

- air temperature;
- temperature of the surrounding surfaces (radiant heat);
- relative humidity;
- air velocity.

Thus, control of these variables is an important factor in the design of a building. Yohanis and Mondal (2010), carried out an investigation of the indoor temperature characteristics on 25 houses over 12 months in Northern Ireland. The study sampled a range of house types across a range of ages. Terraced houses accounted for 37.5%; semi-detached houses, 20.8%; detached houses, 29.2%; and, bungalows, 12.5% of the sample. Buildings less than 15 years old accounted for 13%; between 15 and 30 years old, 25%; between 30 and 60 years old 33% and over 60 years 29% of houses of the sample. This is broadly proportionally representative of house types and age in Northern Ireland. Monitoring included the installation of four thermal sensors, one in the living room, kitchen, hall and bedroom. From the recorded data the average monthly, daily and half hourly temperature for each dwelling was combined to get the average temperature profile for each of the four rooms monitored. The study mapped three distinct energy behaviour groups against the ambient temperature, as shown in Figure 2.

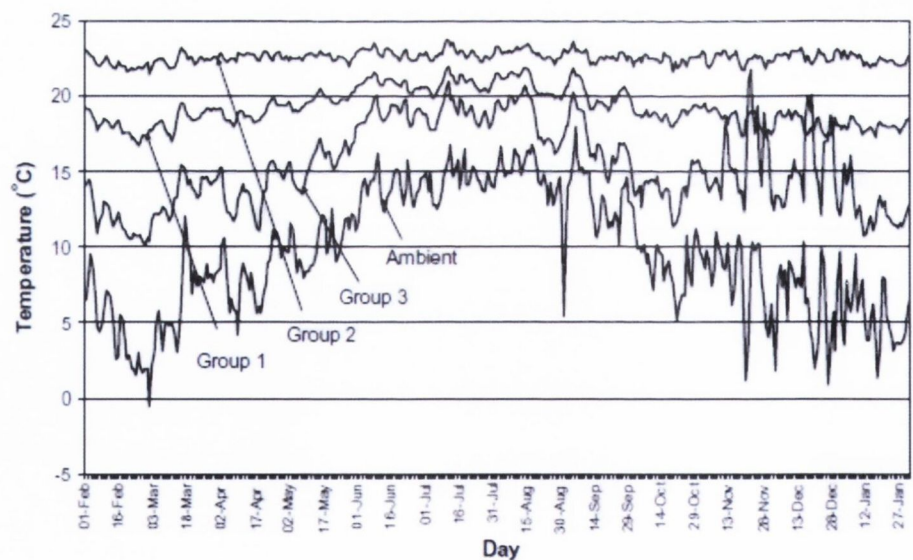


Figure 2 Annual average whole-house temperatures for different home groupings (Yohanis and Mondol, 2010)

Group 1: accounted for 83% of the homes. Here the winter average temperatures were 15 to 20°C and summer average daily temperatures of 20 to 23°C;

Group 2: 14% of the homes maintained an average house temperature of 21 to 23°C all year round and this temperature is almost independent of ambient temperature;

Group 3: the remaining 3% of the homes had an average temperature gradient which closely follows the outdoor ambient temperature.

The study shows that the homes in group 2 are heated to a very high degree all year round with houses maintaining very high levels of thermal comfort. This demonstrates that there is a 'fuel wastage' behaviour amongst some home owners or perhaps in some cases ill health or old age may also be the reason. Other homes demonstrate that they are not heated to an acceptable level and may be as a result of a very poorly insulated house or that the occupants are in a state of fuel poverty. The occupants of these houses may be risk of becoming ill as a result of the lower temperatures. However, the majority of households showed a level of prudent behaviour attaining reasonable levels of comfort throughout the year. Closer analysis showed that the majority of these houses were heated only when occupied.

This study shows that there is a large variability in internal temperature between the households that have very high levels of thermal comfort and those that closely matched the ambient temperature. From the study, it appears that energy usage, particularly for space heating, and probably across the board also varies largely. Therefore, it is important to understand energy use and loss patterns from dwelling to garner a strategy to alleviate the occupants of the thermally uncomfortable houses and also reduce the energy requirement and CO₂ production from the thermally comfortable houses.

2.7 Airtightness

In recent years, improving fabric insulation standards, mechanical efficiencies and a greater understanding of energy use in buildings has augmented the importance of airtightness to whole building energy performance. It is well recognised that airtightness is an important contributor to energy efficiency, thermal comfort and indoor air quality of dwellings (Jokisalo J., 2007, EST, 2005, Pan, 2010, Sherman and Chan, 2003). For these reasons, understanding airtightness is important for new design and energy efficient upgrading of existing buildings.

Technical Guidance Document (TGD) Part L states: *"to avoid excessive heat losses, reasonable care should be taken to limit the air permeability of the envelope of each dwelling"* (DEHLG, 2011 p. 18). Air flow through a building's envelope may be caused by an internal/external pressure

difference as a result of wind and temperature differences or generated by mechanical ventilation systems. Buildings must provide adequate ventilation to maintain healthy and comfortable conditions for occupants. However, the external air entering a building requires energy to equilibrate any temperature differences that occurs between the intern and extern of the building. Therefore, in terms of energy, over supply of air through ventilation, infiltration or exfiltration (air leakage) is not desirable.

A building’s envelope may be described as ‘tight’ if air leakage is small (Webb and Barton, 2002). Jokisalo *et al.*, (2009) describes a modern Finnish detached house with a building leakage rate n_{50} of 0.15ach (air changes per hour) as almost completely airtight, while a leakage air change rate n_{50} of 10ach ($\approx 10 \text{ m}^3/\text{hr}/\text{m}^2$ for cuboid buildings) is leaky. This is an interesting description as Technical Guidance Document Part L (2008) - Conservation of Fuel and Energy (Dwellings) set a “reasonable upper limit for air permeability” of $10 \text{ m}^3/\text{hr}/\text{m}^2$ at 50 Pascals (DEHLG, 2008 p. 20). This was only revised down to $7 \text{ m}^3/\text{hr}/\text{m}^2$ in the 2011 Regulations (DEHLG, 2011). This limit is not onerous when compared to standards in other countries, as shown in Table 1 and the increasingly popular PassivHaus standard requiring an n_{50} of 0.6 air changes per house (ach) (Hodgson and Establishment, 2008).

There have been many studies relating to the characteristics of building airtightness across Europe (Stephen, 2000b, Pan, 2010, Sherman, 1987, Hong *et al.*, 2004, Sinnott and Dyer, 2013, Sinnott and Dyer, 2012) and in particular in the USA where modelled data and over 135,000 single-family detached homes fan pressurisation measurements have been collected and analysed, comparing airtightness in terms of age, size, and construction type (Chan *et al.*, 2005, Sherman and Dickerhoff, 1998, Chan *et al.*, 2013). Chan *et al.*, (2013) sought to standardise comparison between US single-family detached homes using a normalised leakage (NL) rate based on floor area and storey height. NL results were dependent on year of construction, climate zone, duct location and energy efficiency rating of the dwelling.

	Max air permeability ($\text{m}^3/\text{hr}/\text{m}^2$ @ 50Pa)	Max air change rate (Ach @ 50 Pa)
Ireland	10	
Netherlands		6.0
Switzerland		3.6
Germany		1.8 - 3.6
Denmark		2.8
Estonian		3
Finland		1

Table 1 European Airtightness Standards, adapted from (Pan, 2010)

The study found that NL tended to increase in smaller older houses in low-income households. Care needs to be taken when comparing airtightness results, particularly between countries with different construction type, size, ventilation systems and climate. The UK housing stock and climate offers close comparability for this study on an international basis.

In studies of the BRE air leakage database Stephen (1998, 2000b) sought to establish the factors that affect air leakage in UK dwellings and identify typical locations of air leakage. The BRE air leakage database had information on 471 dwellings at the time of the study. The age of the dwellings ranged from pre- 1900 to constructions which were complete in 1994 and construction type of the dwellings also ranged extensively. The fan pressurisation method, also known as the ‘blower door’ method, was used to measure the leakiness of the building envelope. Stephens assessed the database and found that there was sufficient data on the dwelling dimensions to calculate the envelope surface area of 384 dwellings allowing air leakage index ($\text{m}^3/\text{hr}/\text{m}^2$) rather than air changes per hour (ach) to be used to describe the leakage rate. The effects of the shape and overall size of the building are overcome by expressing the leakage as an air leakage index, since the ratio of envelope area to the volume changes with change in building shape. Therefore, the air leakage index is a normalised expression of air leakage allowing for easier building comparisons to be made.

Figure 3 shows the air leakage index ($\text{m}^3/\text{hr}/\text{m}^2$) for each of the dwellings under test conditions at 50 Pascals. There is a large range of leakage rates across the dwelling. However, there is an even distribution about the mean value of $11.5 \text{ m}^3/\text{hr}/\text{m}^2$.

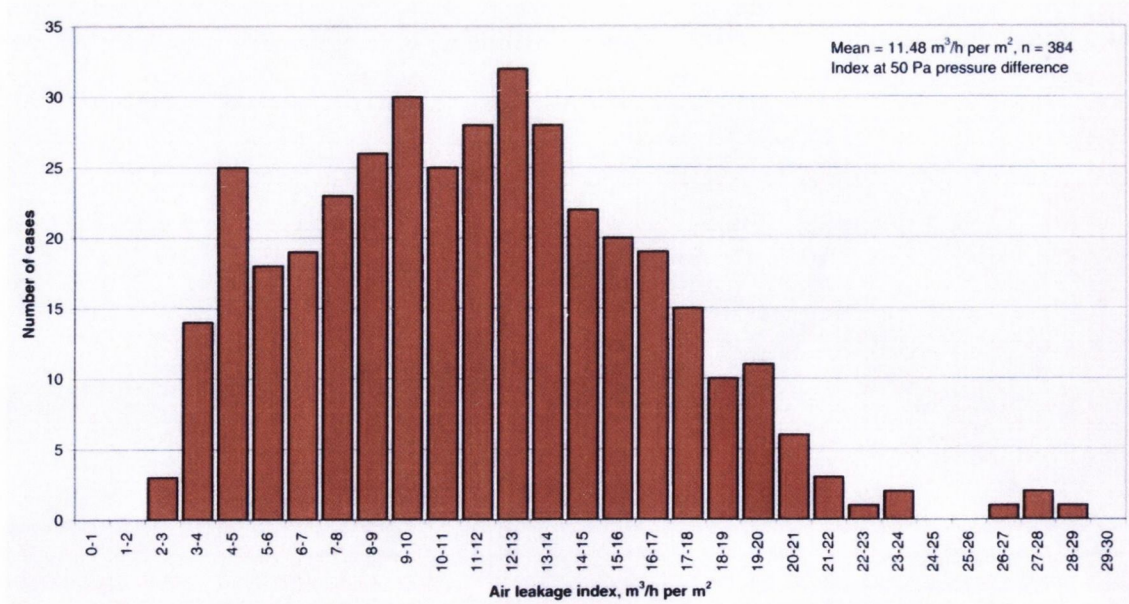


Figure 3 Cumulative distributions of air leakage index (Stephen, 2000b)

There is a common assumption that older buildings are less airtight than modern buildings. When airtightness is compared across the age range, as presented in Figure 4, there seems to be little evidence to support this assertion; although newer houses constructed after 1980 do appear to be slightly more airtight. How the construction type of the building influenced air leakage rates was also assessed. Stephens found that wall construction did have an influence on the envelope airtightness. Figure 5 shows the average differences between solid masonry, cavity masonry, timber-framed, and large panel system (LPS) built dwellings for some 433 dwellings assessed. Masonry wall construction showed the highest leakage rates. This may be due to the number of joints in the block work walls, whereas LPS's consist of precast panels with relatively few joints.

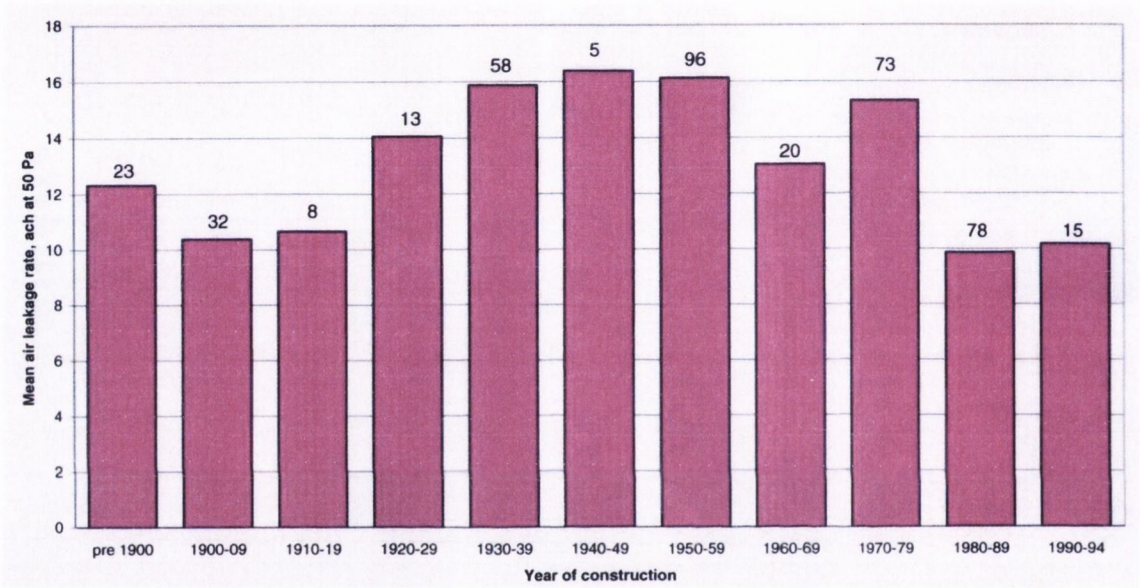


Figure 4 Effect of dwelling age on air leakage rate in dwellings (with number of cases in each range) (Stephen, 2000b)

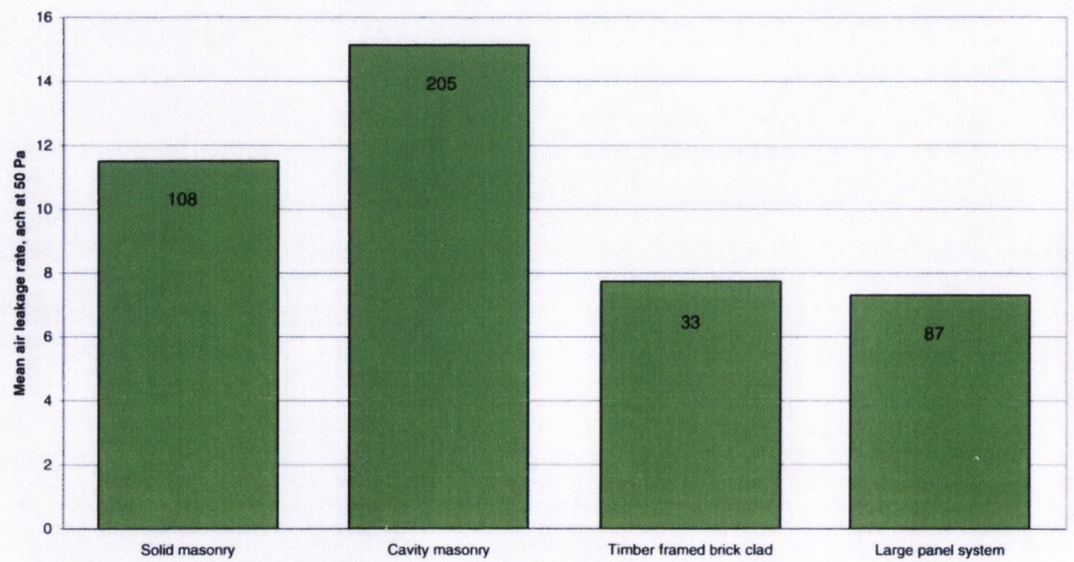


Figure 5 Mean air leakage rates for different wall types (dwellings of all ages, 433 cases) (Stephen, 2000b)

A system of 'reductive sealing' was carried out to establish the main leakage paths from the buildings. This is where the building was tested and then the potential leakage path sealed and the building re-tested. Proportional average values of leakage results from a number of houses are indicated in Figure 6. Doors and windows showed the largest single leakage paths averaging 16%.

There was a large range in results where leakage from windows and doors ranged from 0 – 44% of the total air leakage. Re-testing 79 dwellings after draught stripping was carried out showed reduced the air leakage rate by an average of 8.5%; the range was from zero to about 35%. Air leakage around window boards was one of the key leakage paths. The issue of leakage behind plasterboard dry lining and unsealed service ducts was also noted as part of the study.

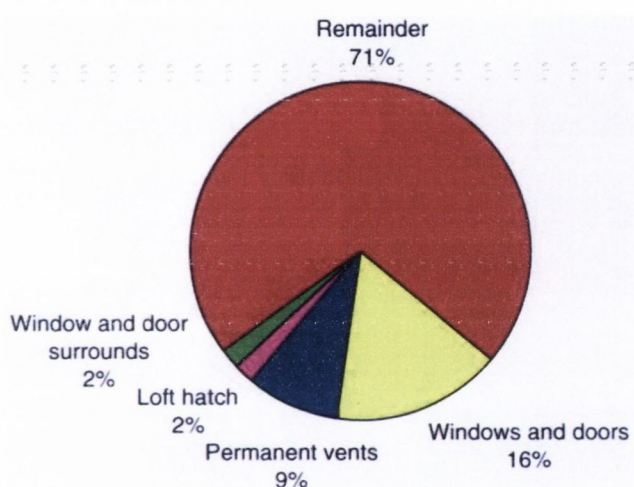


Figure 6 Component air leakage in dwellings (Stephen, 2000b)

The largest air leakage paths, accounting for 71% of the leakage, were classified as 'background air leakage'. These locations included (Stephen, 1998):

- Plasterboard dry lining on dabs or battens (complex routes via skirtings, floor and roof voids, service ducts, etc);
- Cracks, gaps and joints in the structure (open perpend joints, shrinkage gaps and settlement cracks);
- Joist penetrations of external walls (especially inner leaf of cavity walls);
- Timber floors (under skirtings and between boards);
- Internal stud walls (at junction with timber floors and ceilings);
- Electrical components (through sockets, switches, light fittings);
- Service entries and ducts (gas, water and oil pipes, drainage pipes, electric cables);
- Areas of unplastered masonry wall (intermediate floors, behind baths, inside service ducts).

It is difficult to make any realistic estimate of the airtightness of a dwelling of any age, by simple inspection alone. The majority of leakage is associated with the unintentional cracks and gaps in the houses rather than around doors and openable windows. Two major potential sources of air leakage may be unsealed service ducts and plasterboard dry lining on dabs. This would suggest that the quality of construction has a significant influence on the air leakage.

Typical paths through which concentrated infiltration occur include window, letter box and door seals, suspended ground floors, around joist ends at wall connections, conduit and pipework penetrations through the airtight envelope, while up to 70% of the airflow comes diffusely through the myriad of cracks and gaps in the envelope (EST, 2005, Stephen, 2000a, Anderlind, 1985, Kalamees, 2007).

A variety of models have been developed to calculate building infiltration. These models fall into several categories and vary in complexity and accuracy from very simple and approximate techniques to very complex fluid flow dynamics models. The National Methodology used in Ireland for the calculation of energy performance of buildings, DEAP, which may be described as a simple model, includes provision for the assessment of heat loss due to air infiltration. The methodology requires an estimate of design ventilation and infiltration air change rate to determine total ventilation heat loss. DEAP makes a provision for calculating total ventilation heat loss by estimating the design ventilation and infiltration air change rate. DEAP assumes a uniform climate throughout Ireland with an annual mean external temperature of 9.9°C and 7.6°C for heating season (SEAI, 2012a). However, this does not reflect the variability of the Irish climate based on geographical location when attempting to reflect real energy performance. In addition to infiltration due to chimneys, flues, fans and passive vents, DEAP determines infiltration either by:

- a) Estimating 'structural airtightness' based on number of stories, structure type (steel/timber frame or solid wall), floor type (solid or suspended), presence of draught lobby and percentage of door and windows draught stripping; or
- b) Applying a simplified approximation that assumes air permeability and energy consumption are weather independent and there is a linear relationship between the blower door test, q_{50} , as built in service pressure differences over a building envelope and energy consumption. This simplified prediction model is often referred by a number of titles including the rule of thumb, rule-of-20, Sherman's ratio, or the leakage-infiltration ratio. Sherman (1987) attributes the model to Kronvall and Persily and is known as K-P model.

The DEAP adoption of the model, presented in Equation 1 assumes that model gives an estimate of the air change rate per hour (ACH) under normal operating conditions (SEAI, 2012a).

$$ACH_{adj} = \frac{q_{50}}{20} \quad \text{Equation 1}$$

In essence, the model assumes that infiltration is scaled to a pressure differential across the building envelope of 4 Pascals. Scaling accounts for shelter and wind parameters associated with the location of the dwelling. The model is crude and does not account for the “*physical principles at work*” (Sherman, 1987 p. 81). A study by Jokisalo (2007) found improved accuracy could be achieved by replacing the denominator with a regional constant x . However, the adaption of a regional constant for a particular location would require a substantial database for Europe which currently does not exist. Consideration should be given to this methodology as the K-P model was developed using airtightness measurements in the USA where the fabric and properties of the dwellings are different than typical Irish and European dwellings. One example is that 42% of dwellings in Ireland are detached, while over 60% are detached in the US (USCB, 2000, Dennehy and Howley, 2013).

A review by Younes *et al.*, (2012) highlights the need for developments in infiltration calculation to close the current gap between infiltration calculation accuracy and simple modelling techniques. However, in Ireland there is a paucity of real data relating to the airtightness characteristics of existing dwellings from which these improved models can be developed. The perception also exists in Ireland that newer dwelling air-tightness level are better than for older buildings. However, this cannot be confirmed in Ireland because of the lack of empirical data. Chapters 4 and 7 present the results of two separate airtightness studies. The first presents the results of airtightness testing across an age range in Waterford and highlights some interesting findings. The second makes an attempt to develop a simple but accurate model to predict infiltration in Irish dwellings.

2.8 The Case for Upgrading Social Housing

In Ireland and similarly in the UK, it is believed that 75% of the current dwelling stock will still exist in 2050. Energy performance requirements for new buildings have risen significantly in recent years. Of the 1.47 million occupied dwellings in Ireland today, approximately 50% were constructed pre-1980 when minimum insulation standards came into effect (CSO, 2011). As constructed these dwellings fall considerably below current energy related building standards (DEHLG, 2011, DEHLG, 2009).

An analysis by Itard and Meijer (2008) of construction patterns in eight northern European countries showed that there is a declining rate of new construction. The general consensus is that expenditure on renovation is still smaller than new build dwellings though information about renovation is lacking. However, with the decline in new build rates across the eight countries studied, the importance of renovation is predicted to rise.

As indicated in previous research by (Meijer *et al.*, 2009, McDonnell and Sinnott, 2010) the main barriers to upgrading dwellings in the private sector is a lack of knowledge of the benefits and unproven return on investment. This leads to discrepancies between designed and actual energy use in buildings. It is clear that a reduction in building energy use and concurrent CO₂ emissions is an important component to achieving both national and international targets and to comply with EU directives.

There are approximately 300 social housing associations throughout Ireland. Many of these are small and locally based. The remit to provide social housing in Ireland is generally met by the local authorities. Social housing accounts for approximately 9.7% of the total national housing stock (DECLG, 2014, ICSH, 2013). These dwellings vary across all ages from pre- 1919 to current day. The UK has seen a continued increase in social rented sector, which accounts for 17.5% or 3,826,000 households in the UK. This trend is set to be replicated in Ireland. Local authorities and housing associations provide 48% and 52% of the housing respectively (DCLG, 2012). Social housing caters for low income households who normally can't afford their own homes. Consequently, social housing households have a high risk of being in fuel poverty. Healy and Clinch (2002) define fuel poverty as *"the inability to heat the home adequately because of low household income and energy inefficient housing"* (p. 331). While in the UK a household is classified as being in fuel poverty *"if it needs to spend more than 10% of its income to maintain an adequate level of warmth"* (DECC, 2009a p. 2).

An SEI study found that the total number of houses experiencing fuel poverty in 2001 was 227,000, 17% of the overall stock, with 62000 (4.7%) persistently experience fuel poverty (SEI, 2003). Based on 2006 figures, about 3.5 million households, representing approximately 13%, across the UK are currently estimated to be in fuel poverty (BEER, 2008). This issue is likely to be a key political issue in the coming years. Thanks to soaring energy bills nearly 2.3 million households in the UK have fallen into fuel poverty where their power bills leave people's residual income below the poverty line. Typical energy bills have risen 25% from 2010 to 2014 and the trend is likely to continue. About 15% of the typical bill is comprised of green taxes and taxes. It is likely that governments will be loath to pass on more pain or just as likely that they will be punished at the polls if they do so (Fortson, 2014).

There are many and varied perspectives such as, physical (fabric), geographical and spatial, socio-economic, policy and governance on how buildings must be adapted to meet future needs and take their occupants out of fuel poverty. Jenkins (2010) investigated possible overlaps in approaches to deal with the issue of fuel poverty and reducing carbon emissions. The study looks at how social housing projects can be used as an initial 'litmus tests' for such schemes. Jenkins suggests that energy efficient upgrading of social housing has an advantage over private sector houses, since local authorities and housing associations constantly maintain and refurbish their stock.

As a result, these organisations may be able to adopt and refine new technologies more effectively and provide a level of project management that does not exist in the private sector. This suggests a greater impetus might exist for large-scale low-carbon solutions in the social housing sector than in any other sector. Jenkins postulates that retrofitting a large number of social houses, while reducing fuel poverty, could stimulate both the private buyer of low-carbon refurbishment technologies and the manufacturers themselves. He suggests that the increase in sales would, over time, reduce the capital costs of the product, thus widening the market appeal of that particular technology in the private sector.

The case made by Jenkins is reinforced by the Energy Services Directive (ESD) (European Parliament, 2006 p L 114/69) stating that:

Member States shall ensure that the public sector fulfils an exemplary role in the context of this Directive" and that "energy efficiency improvement measures are taken by the public sector, focusing on cost-effective measures which generate the largest energy savings in the shortest span of time.

2.9 Upgrading Approaches and Outcomes

The main drivers of energy efficient upgrading of the existing housing stock are to reduce energy consumption, associated CO₂ emissions, our dependence on fossils fuels, while maintaining or improving occupant comfort. Upgrading the current housing stock can reduce the running costs for occupants and generate the economic benefit from skilled job creation and tax revenue.

Ambitious energy efficiency targets have been set whereby the sector is required deliver a near-zero emissions buildings and 80% reduction in CO₂ emissions from existing stock by 2050. In the interim Ireland is committed to achieving the 2020 targets of 20% reduction in energy consumption and CO₂ emissions. Despite good progress been made towards the 2020 targets it is clear that innovative approaches and enhanced implementation need to be promoted. Gupta *et*

al., (2015) argues that innovative approaches to deep retrofitting of social housing using a whole-house 'deep' approach is required to achieve the 80% CO₂ reduction target.

There is no formal definition of what constitutes a 'shallow' or 'deep' retrofit. Curtin and Maguire (2011 p. 14) propose a general definition of deep retrofit as *'residential energy efficiency measures which result in energy savings of 40%'*, while recognising that the savings could be much greater. Lowe *et al.*, (2012b) say that deep retrofit is a whole house approach typically involving fabric insulation, heating, ventilation and renewables such as photovoltaics to offset the emissions from electricity, or a switch fuel for low carbon heat, example from oil to a heat pump. Jones *et al.*, (2013) describe shallow retrofit as an 'elemental' approach aiming to achieve 10 – 50% CO₂ savings and deep whole-house approach as aiming to achieve CO₂ savings up to 80%, see Figure 7. Shallow retrofitting is often referred to as a 'fabric first' or 'low hanging fruit' approach and generally starts with wall and attic insulation, upgrading windows (double glazing) followed by more efficient boilers. A whole - house 'deep' retrofit approach integrates multiple measures designed for the specific building that may include (Curtin and Maguire, 2011, Jones *et al.*, 2013, Loveday and Vadodaria, 2013):

- building fabric (attic, cavity, internal and external wall and floor insulation);
- building airtightness and draught proofing;
- Ventilation (MV/MVHR systems) and humidity control;
- Windows (double/triple/vacuum glazing) and doors;
- Heating system (highly efficient boilers, heat pumps);
- Energy management and heating controls system;
- Replacement of inefficient appliances and fittings (incandescent lighting, old fridge);
- Fuel switching (e.g.solid fuel to gas);
- Advanced technologies: Innovative materials (e.g. phase change materials);
- Renewables (PV, Solar thermal, Ground source heat pump, micro wind, micro CHP).

In an attempt to formalise energy efficient techniques the National Standards Authority of Ireland have developed a Code of Practice (NSAI, 2014) that provides holistic approach and technical guidance on dwelling energy efficient retrofit.

However, Jones *et al.*, (2013 p. 535) states that *'multiple measures tend to follow the law of diminishing returns, where energy saving from a combination of measures is not necessarily the sum of savings from individual measures.....and can prove costly and disruptive to the household'*. Therefore in the context of Article 4 of the Energy Efficiency Directive, (European Parliament, 2012) when developing policies and specifying upgrading measures care needs to be taken that the stimulation of deep retrofitting of dwellings is cost-effective.

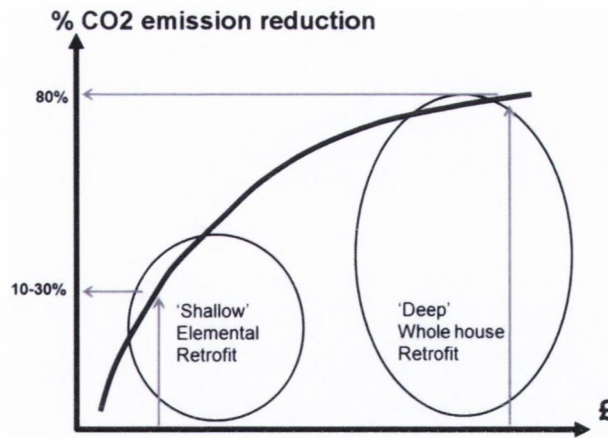


Figure 7 Estimated cost associated with CO₂ emission reductions (Jones *et al.*, 2013)

For Ireland's Home Energy Saving (HES) the average expenditure on an upgrade is around €3,000 per applicant, including the grant. Therefore very few homeowners are presently carrying out deep retrofits. Exploring the barriers to uptake of national retrofit schemes a study by the SEAI (2013) found that homeowners did not view deep retrofit as a well-defined concept with specific objectives. Therefore, there is no rationale associated with large scale upgrading but owners prefer to associate these measures as incidental when undertaking home improvements and modernisation. This is echoed in the findings of Simpson *et al.*, (2015) who found that life events and access to funding has a strong influence on the work that homeowners carried out.

2.9.1 Fuel Switching

It is important to remember that there is not a linear relationship between all dwelling energy use and CO₂ emissions. Increasing fabric insulation will reduce the requirement to produce heat energy for example by burning fossil fuels. However, further CO₂ saving can be made by fuel switching to a less carbon intensive fuel solid fuel to gas or biomass. Jones *et al.*, (2013) argues that fuel switching is the most cost effective way of making CO₂ emission savings. Table 2 demonstrates that there is a potential to save up to 61% and 25% of CO₂ emissions by switching from electricity and heating oil to natural gas respectively. In Ireland there are approximately 300,000 dwellings in urban settings served by natural gas have oil fired central heating, of which approximately 33% are located within 20m of the natural gas pipeline (IAE, 2013).

		Electricity	House coal	Heating Oil	Natural Gas
	kg/CO ₂ /KWh	0.522	0.361	0.272	0.203
Electricity	0.522	0%	-45%	-92%	-157%
House coal	0.361	31%	0%	-33%	-78%
Heating Oil	0.272	48%	25%	0%	-34%
Natural Gas	0.203	61%	44%	25%	0%

Table 2 Fuel CO₂ Intensity (adapted from (SEAI, 2012b))

The Irish Academy of Engineers (IAE) (2013 p. 11) believe that 1.3 Mt/year of CO₂ emissions can be offset by replacing 75% of the rural oil-fired central heating load with heat pumps. Heat pumps would save future CO₂ emissions by negating the need for rural oil deliveries.

2.9.2 Rebound and Prebound Effect

There is increasing awareness of the performance gap between predicted and actual savings following energy efficient upgrading. The difference is often attributed to a phenomenon termed 'rebound' or 'take back' effect (Chiu *et al.*, 2014, Gram-Hanssen, 2014, Tweed, 2013, Lowe *et al.*, 2012a, Jones *et al.*, 2013). Galvin (2014 p. 515) defines the 'rebound effect' in broad terms as *'the proportion by which the consumption of energy services increases as a result of an energy efficiency upgrade, and usually in relation to the proportionate increase in energy efficiency'*.

In an ex-post- billing analysis of gas consumption for a sample of dwellings in the SEAI Home Energy Saving (HES) residential retrofit scheme Scheer *et al.*, (2013 p. 35) found a mean reduction in gas demand of 21%. However, this represented as *'shortfall of approximately 36 ± 8% between technical potential and measured savings'*. The study attributes much of this shortfall to direct and indirect rebound effects. Direct effects occur when an occupant increases comfort level in lieu of energy savings, while indirect rebound may be as a result of the cost of fuel decreasing or spending savings on other services. To estimate the effect of 'direct rebound', Sorrell *et al.*, (2009) reviewed residential heating result from 12 'quasi- experimental' studies. The study attributes the estimated temperature take back of 0.14 °C to 1.61 °C to both physical changes to the dwellings and behavioural change. The analysis found that the temperature 'take back' was higher for low income householders and where low internal temperatures were recorded prior to upgrading. The associate loss of energy savings associated with the temperature 'take back' was ranged from 0% to 100%, with a mean of around 20%. This is similar to the findings of Bojic *et al.*, (2014) concludes that direct rebound effects are unlikely to exceed 30% in OECD countries.

Kelly (2011) analysed 2531 cases of domestic electricity and gas consumption data in the UK. The study found that the higher the SAP rating of the dwelling the greater 'propensity to consume more energy' and the reverse was true for buildings with a low SAP rating. Sunikka-Blank and Galvin (2012) compared the calculated energy performance rating (EPR) against measured consumption of 4300 dwellings in Germany. The study found that for dwellings with an EPR < 100 kWh/m² dwellings on average consume more energy than predicted by the EPR; typical of the rebound effect. However, overall the average measured consumption was 30% below the EPR, ranging from 17% to 60% for dwellings with an EPR of 150 kWh/m² and 500 kWh/m² respectively. This phenomenon of using less energy than predicted is introduced as the 'prebound effect'. The

prebound effect is likely to be higher as the EPR increases. Where this situation exists the economic viability of energy efficient upgrading becomes questionable.

Galvin (2014) concludes that the term 'rebound effect', for domestic consumption, means different things in different publications. The paper proposes the development of 'careful' definitions of the "classic" rebound effect, energy savings deficit (ESD) and energy performance gap (EPG).

2.10 Warm Front Energy Efficiency Scheme

The Warm Front energy efficiency scheme was launched in England in 2000. The scheme provided funding for a broad range of insulation and heating improvements for low-income vulnerable households in private tenure at risk fuel poverty (NAO, 2003). Other driving forces behind the scheme were to improve the buildings energy efficiency, reduce energy use, and lower CO₂ emissions. In 2001, the 'Health Impact Evaluation of Warm Front' study was commissioned to investigate the effect of the Warm Front scheme had on resident health in England. Thermal comfort data, including temperature and occupant thermal comfort, of some 2500 households was collected. This data led to a number of studies into the impact the Warm Front scheme, had on the thermal comfort levels of the occupants, the energy efficiency of the upgraded houses and the impact on the airtightness in English Dwellings. The studies were based on the pre-2005 scheme which allocated funding for cavity wall insulation, loft insulation and draught proofing. In 2005, the scheme was upgraded to include funding for gas central heating upgrades. Comparisons were made between pre- and post-improvement households measured in the same winter.

A study by Hong *et al.* (2006) examined the impact that the Warm Front refurbishment scheme had on the space heating consumption of the dwellings. From a total 2659 dwellings, they used 2901 sets of fuel consumption data (1255 pre-intervention, 1162 post-intervention and 242 both pre- and post-intervention) were also collected. The total fuel consumption for each house was recorded over the same 2–4 week period that the house was monitored for temperature by reading the gas and the electric meters each time when the data loggers were placed and removed. Utility billing data for 1–2 year period was further obtained from utility companies for 100 surveyed properties with the consent of the householders.

In 2001, the average SAP rating of the UK housing stock was 51, with just over 9% of the dwellings having a SAP rating of 30 or below and 8% had a SAP rating in excess of 70 (ODPM, 2003 pp 18). The average SAP rating for pre-Warm Front dwellings was 41 which increased to 62 post-Warm Front as shown in Figure 8. It is worth noting that post- intervention a large proportion of

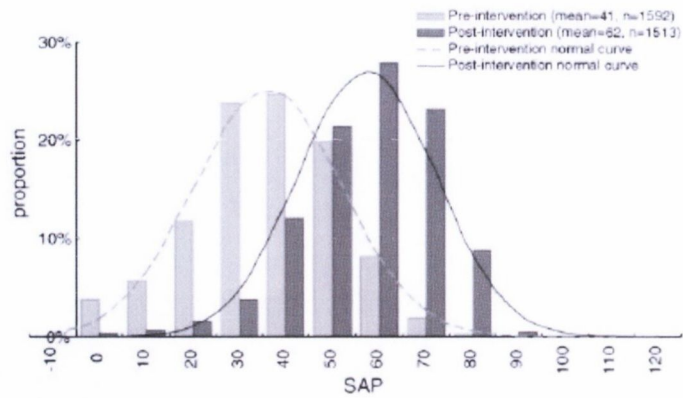


Figure 8 SAP rating pre- and post- Warm Front (Hong *et al.*, 2006)

dwellings still had a SAP rating below 41. Hong assessed the energy efficiency of the upgraded houses based on the energy consumed for space heating to raise the internal temperature by 1°C before and after the energy efficiency improvements.

Modelling post- intervention space heating load, Hong found a theoretical potential of 25% decrease in fuel consumption as shown in Figure 9(A). This theoretical assumption was not supported by the monitored normalized space heating fuel consumption, as shown in Figure 9(B). In fact the longitudinal normalised space heating revealed a mean increase from 110 to 120 Wh/K/m²/day.

Another reason why an overall reducing in energy consumption was not recorded was due to occupant’s ability to afford to heat their houses to a high standard and are less conscious of energy costs. Whereas, in the case of fuel poor households a larger reduction in energy consumption may have been recorded as this costs puts a large burden on the household. Problems were also highlighted where the upgrade works included installation or upgrade of gas central heating which incurred placing of pipework causing holes and increasing air permeability.

Hong *et al.* (2009) examined the impact that insulation and heating improvements, through the Warm Front scheme, had on the thermal comfort levels of the occupants. A self-report thermal comfort diary was used to record the thermal comfort perception and monitored sitting room and bedroom temperatures. This was carried out twice per day for 11 consecutive days. The thermal

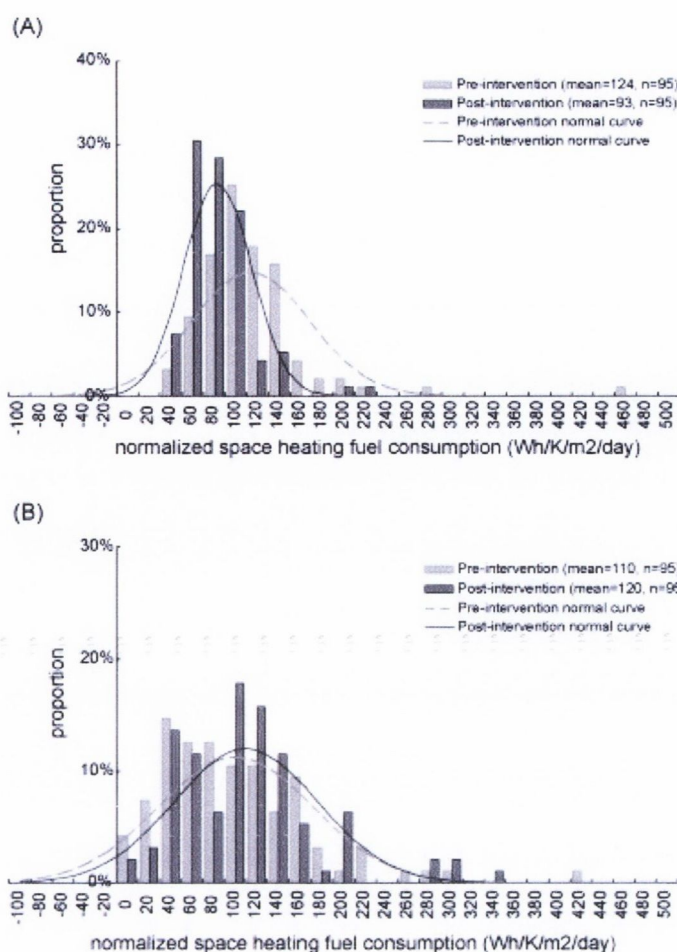


Figure 9 Normalised space heating consumption between pre- and post- Warm-Front (A) Modelled and (B) Monitored (Hong *et al.*, 2006)

comfort perception records were based on the ASHRAE Standard 55 and ISO Standard 7730. From the initial 2500 households partaking in the study, 2399 thermal diaries were recovered. Over the 11 day study period an average of 8.5days recordings were recovered from each household. Dwelling types ranged across the board from detached, semi-detached, terraced and flats.

Householders recorded the internal temperature from liquid crystal temperature strips as part of their comfort diary in both the living room and the main bedroom. Automatic dataloggers were also installed in 48% of houses and used to record the indoor temperature at half-hourly intervals in the two rooms. Comparisons between the temperatures logged by the occupant and the data loggers were on average 0.3°C lower than the logger monitored with a large standard deviation of 2.2°C . This deviation may have been as a result of inaccurate reading of the strips or that strips may have come in contact with a cooler surface before reading.

Figure 10(a and b) show the variability in the comfort valve (CV) between pre- and the post-Warm Front dwellings. The figure compares the CV by the room type, time of day and age of the

householder. The shaded band indicates the thermally 'comfortable' range ($-0.5 \leq CV \leq 0.5$). It is noted that there is an improved thermal comfort condition across all the groups and their mean values all within the 'comfortable' range. The retrofitting process increased the mean indoor temperature by 1.9°C from 17.1°C to 19°C with a relatively high standard deviation of 2.3°C and 2.1°C respectively. Correspondingly, almost 79% of respondents found that post- Warm Front thermal comfort to be 'comfortable' compared to 36.4% of the pre-Warm Front respondents.

The study seems to show that, on average, there was a significant increase in thermal comfort levels post- Warm Front. It also suggests that this have a have positive effect on the standard of living and the health of the vulnerable occupants. However, the study does not quantify the cost the actual work done to be buildings. It does not match how particular work affected the internal increase of temperature. External temperature monitoring was poor giving just average temperatures over the period and taking little account of the temperature profile for different geographical locations. The study was carried out over a very short period of time and is between November and April but it does not break down the difference in temperature over that time. Though the average temperature increases look good there is a relatively large standard deviation showing that the retrofitting works had a varying degree of effect. Taking the 19°C minus 2.1°C standard deviation, results in a temperature of 16.9°C which is below normal thermal comfort levels.

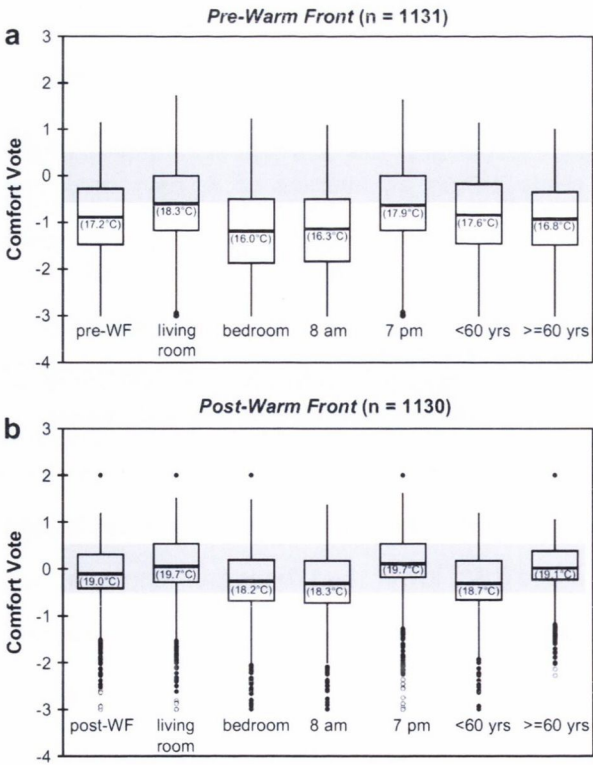


Figure 10 Thermal comfort levels (a) pre- (b) Post Warm Front (Hong *et al.*, 2009)

2.11 Retrofit for the Future (RftF) programme

In 2009 the UK's Technology Strategy Board (TSB) (now Innovate UK) launched the £17 million Retrofit for the Future programme to demonstrate and evaluate innovative approaches to deep retrofitting of social housing. Social housing represents over 17% of UK housing stock (DCLG, 2015). The project set out to achieve an 80% reduction in CO₂ emissions against an average 1990 baseline of all existing domestic stock, using a variety of whole-house retrofit approaches. The resulting CO₂ emissions and primary energy targets were (TSB, 2013):

- 17 kgCO₂/m²/year using SAP 2005 (equivalent to 20 kgCO₂/m²/year using PHPP);
- 115 kWh/m²/year.

Following initial selection in phase one, 86 projects were chosen for phase 2, covering 119 dwellings across the UK. The dwellings chosen were relatively homogeneous when compared to the entire UK housing stock. They were awarded up to £150 000 to demonstrate the effect of deep retrofitting each home. Different subsets of information and varying experimental procedures were conducted and gathered in each dwelling. These included testing building fabric conditions, long term energy use and internal environmental conditions, occupant comfort, experiences and post- occupancy evaluations (POE) (TSB, 2014).

To achieve the carbon reduction a range of deep retrofit approaches were devised incorporating a range of energy efficiency techniques and renewable technologies. This included super insulated and airtight external fabric, mechanical ventilation with heat recovery (MVHR) to 75% of the upgraded dwellings, high efficiency boilers, biomass boilers, heat pumps, solar thermal and solar PV. For optimum execution of a deep retrofit strategy it was found that occupants should vacate their dwellings to enhance the quality of work (TSB, 2013).

Useful data from just 86 of the retrofitted dwellings was available for analysis. The main purpose of the analysis was to establish the effectiveness the deep retrofitting by establishing energy reduction and CO₂ savings compared to predicted targets. Post- retrofit consumption and emissions were available for 45 dwellings. The study found the majority achieved 50% - 70% CO₂ savings while only three of the dwellings achieved the RfF target. Airtightness improved in 90.7% of the sampled dwellings with a mean post- retrofit air permeability of 5.5 m³ /hr/m² @50 P.a. (TSB, 2013).

Gupta *et al.*, (2015 p 446) summaries the project saying:

despite generous funding and professional expertise, decarbonizing existing housing will not be particularly easyand the 'whole house' approach adopted in the RfF programme rarely delivered radical energy reductions.

The outcomes of the programme highlight the complexity of the delivery of deep carbon savings from whole house energy retrofitting. Gupta *et al.*, (2015) questions the economic viability of house-by-house deep retrofitting and proposed localised area-based approaches as a way of achieving economies of scale. The paper highlights the high level of project management and broad scope of works which makes whole house approaches challenging.

2.12 Calebre Project

The £2 million Consumer-Appealing Low Energy technologies for Building Retrofitting (CALEBRE) project (2008-2013), funded by EON and RCUK Energy Programme brought together the multi-disciplinary expertise of six leading UK universities. It was established to evaluate a number of innovative retrofit methodologies for solid wall dwellings and gather occupant perspectives of the retrofits. The barriers and challenges associated with retrofitting and thermal comfort evaluation was a key component of the project (Loveday *et al.*, 2011, Loveday and Vadodaria, 2013).

Haines (2014), Haines *et al.*, (2013) and Vadodaria *et al.*, (2010) studies were centred on semi-structured interviews of 20 owner-occupied households (66 occupants). The study took an occupant centred approach, in conformance with ISO 9241-210: 2010. The purpose of the study was to establish the reasons why the householders carried out past improvements to gain their perspectives on the process to appropriately modify selected technologies for the technical aspect of the CALEBRE project.

Many of the householders cited architectural character lacking in newer properties as the reason why they bought an older dwelling. They also felt that the workmanship on older houses is better than for new homes.

The main findings of the study were that householders desire to improve building quality and occupant comfort outweighed the intention of saving money. Householders chose professionals to work on their homes based on price, trust, recommendation and length of time they knew the professional. Very few of the householders were prepared to move out of their property and preferred to carry out upgrading on an on-going piecemeal basis. Consequently they were prepared to tolerate considerable disruption including living without kitchens and bathroom for up to a number of weeks.

Some of the main motivations householders cited for retrofitting included repair, thermal discomfort, personal satisfaction and energy efficiency. A number of the main barriers to upgrading were affordability, finding the time and correct tradesperson and life events. Unexpected delays caused considerable stress and in hindsight some of the householders would not have commenced the project.

In general there was a negative attitude to mechanical ventilation and householders were keen to maintain naturally ventilated air flow, even if there was excessive heat loss. They felt that draughts kept their homes adequately ventilated and healthy (Banfill *et al.*, 2012).

The study found that clear communication is key to convince householders of the benefits of an airtight house with mechanical ventilation. There is a need to better understand the needs, values and aspirations of householders. Competent professionals who are willing to explain the rationale of the particular retrofitting strategy is necessary to satisfy the expectations of the householders.

2.13 Welsh ARBED

The Welsh ARBED regeneration programme (Welsh Government, 2013) was established in 2009 to bring environmental, social and economic benefits to Wales by providing finance to local authorities and social housing landlords to undertake energy efficient upgrading of their existing stock. Approximately £60 million was invested in phase one funding measures to over 7500 households including solid wall insulation, solar panels and heat pumps to make communities in deprived areas of Wales more energy efficient and reduce the impact of fuel poverty. It also supported the development of local supply chains for the installation of the measures.

Jones *et al.*, (2013) analysed the potential energy savings and costs associated with a subset of the upgraded dwellings. Though initially set up as a 'whole house' upgrade programme most of the upgrades were elemental with 905 properties receiving one measure, 240 two measures and two received three measures. External wall and attic insulation were the most common techniques deployed. The analysis showed that for the 502 dwellings that availed for fuel switching from electric to gas there was 55% energy savings for an average cost of £3000. Excluding fuel switching the average cost of the measure was £7771 and the average savings 25.3% calculated using the Energy and Environmental Prediction (EEP) model which was developed by the Welsh School of Architecture in the early 2000's (Jones *et al.*, 2000).

Phase 2, 2012 – 2015 is partly funded by the European Regional Development Fund (ERDF) aims to improve the energy efficiency of a minimum of 4800 existing and reduce a minimum of 2.54 ktCO₂ emissions.

2.14 Monitoring Analysis and Data Handling Techniques

The dynamic nature of the environment in which buildings function much be considered when evaluating whole building energy use. The section presents the methodologies used to verify the dwellings energy use and any saving made as a result of the energy efficient upgrading in the context of the environment and occupants.

Monitoring and Targeting (M&T) and Measurement and Verification (M&V) are common energy management techniques used to identify trends in consumption. Both methods have a number of similarities but have distinct outcomes. The basic principle of M&T is that energy monitoring can be used to predict energy consumption based on historical data. This future consumption is then measured against expected data. The objective of M&V is to establish the change in energy use as a result of some intervention. Measurements pre- interventions are used to project energy use patterns without any intervention. Post- intervention measurements are then used to verify savings.

The energy management industry is relatively new and though several best practice guidelines have been developed, techniques for both M&T and M&V are still evolving. The most recognisable M&V methodology, predominantly used in the commercial sector, is the International Performance Measurement and Verification Protocol (IPMVP). It is important to measure energy consumption against some form of threshold to establish a key performance indicator (KPI) in both techniques. This study is primarily focused on M&V and the following section describes the fundamental concepts of degree days, baseline, performance line and CUSUM analysis which are commonly used.

In this study energy consumption data was recorded over a 36 month period. This poses issues when assessing data which is influenced by climate variables. Section 2.14.1 outlines the methodology used when comparing energy consumption datasets over a long period of time.

2.14.1 Heating Degree Days

Dynamic external weather conditions are considered to be one of the dominant causes of variability in building energy consumption. This does not just include air temperature but also, insulation, humidity, wind speed, precipitation, cloud cover, internal temperatures, casual gains and air infiltration. Heavy computer based full thermal simulation models are required to process

the combined impact of all these parameters. Though simulation can include this wide number of parameters it cannot accurately predict energy use. This is due to the difference between design and real in situ thermal capacity, occupant behaviour, addition of systems and appliances over time and positive or negative system efficiency over time. Thus, this study utilised a simplified degree day characterisation method to include the effect of climate variables. Degree-day and CUSUM analysis are an established industry procedure in building energy performance analysis (CIBSE, 2006b, The Carbon Trust, 2007). Degree days use a number of simplifying assumptions to make the process easy to use and understand.

Degree days are considered to be a versatile climate indicator and a good reference point against which energy consumption can be measured. Degree days can be expressed in two forms: Heating Degree Days (HDD) and Cooling Degree Days (CDD). Ireland's temperate oceanic climate and average annual temperature of about 9⁰ Celsius (C) summer mean maximums and minimums of about 19⁰ C and 2.5⁰C respectively means that dwellings are predominately naturally ventilated and have no mechanical cooling (MET Eireann, 2012). Therefore, in this study only HDD are considered.

The basic principle is that calculation of long term building energy consumption is proportional to the difference between internal and external temperature. Degree days are essentially the summation of positive temperature differences between a reference temperature and the outdoor air temperature over time and expressed on a daily or monthly basis as shown in Equation 2 and Equation 3 respectively.

For the calculation of daily degree days (HDD_d)

$$HDD_d = \frac{\sum_{j=1}^{24} (T_{base} - \bar{T}_{outside,j}) ((T_{base} - \bar{T}_{outside,j}) > 0)}{24} \quad \text{Equation 2}$$

where

T_{base} is the base temperature

$\bar{T}_{outside,j}$ is the outside temperature in hours, j.

An alternative way to express Heating Degree Days per month is:

$$HDD_m = \sum_{d=1}^{Dm} (T_{base} - \bar{T}_{outside})^+ \quad \text{Equation 3}$$

where

$\bar{T}_{outside}$ = mean daily temperature on day d;

T_{base} is the base temperature;

+ directs that only positive values are added.

Hence degree days combine the extremity and duration of outdoor temperatures. This reference temperature is commonly referred to as the “base temperature”, or “balance point”. In HDD theory, this base temperature is the outside temperature above which a building does not require heating to maintain occupant comfort. Eto (1985) defines the base temperature as corresponding to the best fit of energy use to degree-days line, measured using R^2 squared statistic. Therefore different buildings can have different base temperatures. In reality, the base temperature is actually influenced by the design and use of the individual building. Hargy (1997) states that if a buildings thermal conductance is reduced by increasing thermal insulation the internal base temperature can also be lowered. For simplicity, the UK and USA use ‘default’ base temperature values. However, the UK use a default base temperature value of 15.5°C , whilst in the USA the default is 18°C . Caution needs to be taken when using the R^2 method, as highlighted in Section 2.14.2.

Figure 11 demonstrates the average daily temperature profile for Kilkenny in 2013. Assuming a base temperature of 15.5°C the total number of heating degree days for 2013 are represented by the shaded area.

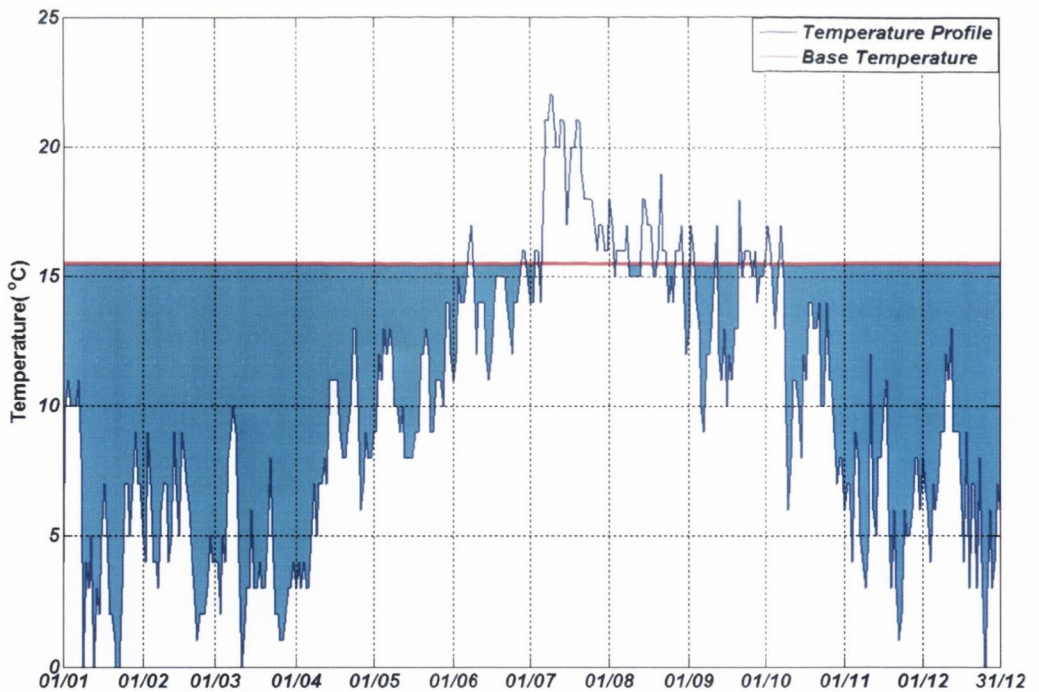


Figure 11 Average daily temperature for Kilkenny City in 2013

As a building loses heat a proportion of the energy is replaced by incidental gains from natural sources such as solar gains. Artificial sources include appliances and anthropogenic activity. Also, air absorbs heat as diffuse infiltration occurs through the envelope; unaccounted for this may lead to an overestimation of the energy impact (Younes *et al.*, 2012).

Therefore, the energy balance is not simply the internal-external temperature difference and the base temperature will not be desired internal temperature (set point temperature) for the buildings but rather somewhere below it.

(CIBSE, 2006a) sets out mechanisms by which to establish internal heat gains from occupants, equipment, motors, cooking and other domestic appliances. However, calculations can be cumbersome, subjective and vary based on occupant profile. (Zhou *et al.*, 2012) examined city scale heat generation in Indianapolis, USA and estimates that the mean anthropogenic heat discharge can be in the region of 32 W m^{-2} . Though concern has to be given to the accuracy of the model, it is clear that considerable heat gains can be attributed to anthropogenic activity in buildings. Calculation methodologies like DEAP use utilisation factors to balance these gains.

Degree-days offer a simplified approach to balance these heat gains. Degree-day calculations typically use a standard internal base temperature of 15.5°C which approximates the heat gains as equivalent to 3°C . This is consistent with analysis of the Warm Front programme which found internal gains were equivalent to 3.2°C (Hamilton *et al.*, 2011).

Ireland does not have a degree day map unlike in the UK which has published monthly degree day data for 18 locations. Hargy (1997) was the first to try to develop accumulated temperature data map for Ireland. He based the map on location northing, easting and altitude from the 40 Met Eireann weather stations that were operational at the time. This is recognised as a first step to generating a degree day map for Ireland. This work was developed by Fealy and Fealy (2008) but still remains to be adopted as a national standard. Thus local calculation is still required.

Calculation of External Temperature $\bar{T}_{outside}$

In an attempt to approximate the integral:

$$HDD_d = \int (T_{base} - \bar{T}_{outside}) dt \quad \text{Equation 4}$$

to simplify the calculation ASHRAE (2009), CIBSE (2006b) and Hargy (1997) state that $\bar{T}_{outside}$ can be calculated as:

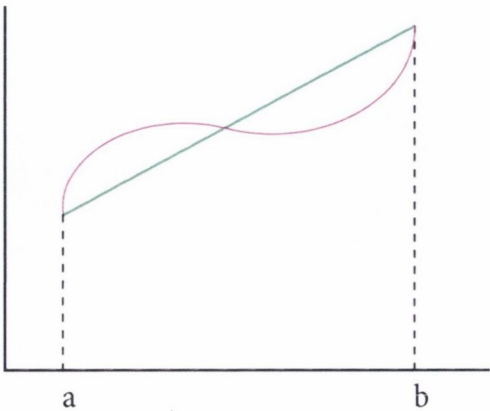
$$\bar{T}_{outside} = \frac{T_{max} - T_{min}}{2} \quad \text{Equation 5}$$

where: T_{max} is the maximum temperature and T_{min} the minimum temperature over time, t .

This is sometimes described as the standard triangle method. The method lacks detail relating to temperature duration. Though it makes the degree day calculation simpler and can be done by hand it can only make a reasonable assumption of the average temperature. Therefore, when using published degree day data it is important to understand the calculation process.

For this research the degree data is generated using an online software tool, degreedays.net, to more accurately generate degree day data. This processes data from Weather Underground. Based in San Francisco Weather Underground is a commercial weather service that provides real-time weather information via its website www.wunderground.com. For this study ,the weather station which supplies the data to Weather Underground is located in Kilkenny City, less than 4 km from the study buildings. Data is generated by a Oregon WMR 928 weather station with air temperatures measured using max and min electronic Oregon sensor thermometers in accordance with BS EN 692:2005+A1:2009. The sensors are housed in a Met Éireann standard Stevenson Screen i.e. a typical standard exposure. Temperature readings are reported to Weather Underground every 15 minutes. BizEE Software Ltd, a UK based company, uses this data to calculate degree-days for a range of base temperatures using the integration method. The software calculates degree-days using the average temperature for an interval and the interval time; in this case 15 minutes. The average temperature is calculated using the trapezoidal rule and approximating the region under the graph as:

$$\int_a^b f(x)dx \approx (b - a) \left[\frac{f(a) + f(b)}{2} \right] \quad \text{Equation 6}$$



The required degree day data is accessible through the BizEE website degreedays.net.

Degree days use a number of simplifying assumptions to make the process easy to use and understand. Therefore, their use can only achieve approximate results.

2.14.2 Bivariate Linear Regression Analysis

The most common method of consumption modelling in energy M&T and M&V is the 'performance line model' (The Carbon Trust, 2012, The Carbon Trust, 2007, CIBSE, 2006b, Lewry, 2012, Sonderegger, 1998). The performance line is generated as the linear relationship between energy consumption plotted on y-axis and degree days plotted in the x-axis. A best-fit straight line plotted through the data using linear regression analysis is given by:

$$E = \alpha + \beta HDD \quad \text{Equation 7}$$

where:

- E is the energy consumption;
- α is the y-axis intercept;
- β is the gradient of the performance line; and
- HDD are the degree days for the period.

When plotting the performance line it is usual to use the residuals to establish the, R^2 , statistic for the fit. The coefficient of determination, R^2 , is an intuitive measure of how well a linear model fits a set of observations. In building energy performance analysis it is common to accept that R^2 with the data such as HDD. Generally it is taken that $R^2 > 0.75$ indicates a reasonable correlation, > 0.85 indicates a good correlation and > 0.9 is very good correlation. This paradigm is limited given that R^2 cannot determine whether the coefficient estimates and predictions are biased. To evaluate the energy performance the R^2 values should be evaluated in conjunction with the Residuals Plots, and P-values to estimate the probability of rejecting the null hypothesis of a study question when that hypothesis is true.

2.14.3 Baseload and Base Temperature

Energy consumption in buildings can be divided into weather-dependent (heating) and weather-independent (water). This weather-independent consumption is often referred to as "baseload" consumption. In degree day analysis it is common to assume that baseload energy is constant throughout the year.

Estimation of baseload can be achieved by either:

- Assuming consumption during the summer is not heating related and extrapolation this consumption across the year;
- Utilising the linear regression analysis.

In theory, the performance line enables disaggregation of the weather and non-weather related energy consumption. The intercept, α , can be used to estimate the non-weather related consumption. Care needs to be taken when establishing the baseload as it is highly dependent on the base temperature. Figure 12 demonstrates baseload estimation for dwelling F in the study at 15.5°C and 18°C base-temperature. Here it is clear to see that baseload estimation is very different even though the R^2 correlation is reasonably good for both base temperatures.

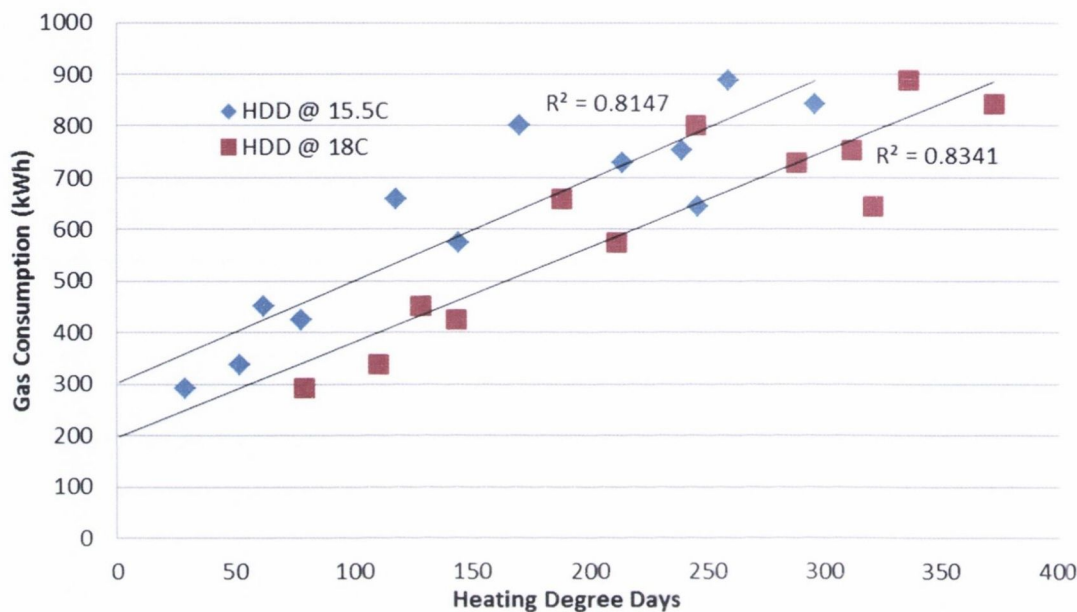


Figure 12 Estimation of dwelling F baseload for variable base temperature

In an attempt to establish suitable base temperatures in this study pre- and post- upgrading, R^2 values for a range of base temperatures from 12 to 23°C were calculated for each dwelling. For the 9 dwellings it was found that R^2 values varied little through the iterations and that 14.5 – 17°C produced the best correlations. Understanding the relative accuracies of the methodology to simplify comparison standard UK base temperature of 15.5 °C was applied to all the dwellings.

2.14.4 Weather Normalisation

A difficulty arises when comparing multi-year energy consumption. Comparing one year to the next allows for only change between those reference years. If both years were uncharacteristically warm or cold the results would be skewed. Degree day ratio-based weather correction, commonly known as 'weather normalisation', allows the adjustment of measured energy consumption. In theory this allows a like for like comparison over a normal weather period and reporting can report as standardised annual energy consumptions. Once normalised energy consumption is established it can be used as normalisation of performance indicators (NPI).

According to Day (2006) performance line analysis is suitable for monthly but not daily data as the performance lines would cover up the non-linear day to day behaviour of the building due to daily variations in occupancy, thermal mass, intermittent heating and other gains or fluctuations from visitors. Therefore, it is not sensible to compare normalised data from one week or month to the next. This is further demonstrated in Section 6.4.1.

2.14.5 CUSUM Analysis

CUSUM is short for 'cumulative sum of the difference'. The 'difference' refers to the differences between the predicted and measured energy consumption. In Figure 12 (above) the distance from the measured and predicted energy use (performance line) are the residuals. Rather than comparing an observation with a target value the methodology simply involves taking the cumulative sum of the residuals, as shown in Equation 8. The CUSUM methodology is used extensively as an energy management tool (CIBSE, 2006b, The Carbon Trust, 2007).

$$CUSUM_j = \sum_{i=j}^j (E_i - \hat{E}_i)$$

Equation 8

Degree day theory is a practical tool in energy management as it allows for the generation of performance lines and the ability to compare year to year energy consumption. Degree day values are heavily dependent on the choice of base temperature. In practice energy gains will fluctuate in real terms resulting in a variable base temperature. Therefore there is an inherent error in the simplified degree day theory. The concept of a Variable base degree-day (VBDD) model is well established but the process is complex and actual internal situations leading to a true base temperature are impossible to determine. Though errors are inherent in the average overall base temperature (Day, 2006 p.p. 82) states though the errors can be analysed "*such analysis is generally beyond the needs of the general user*". Day and Karayiannis (1999) highlight calculation inaccuracies increase as measurement timescale decreases; monthly energy estimates tend to be more accurate than daily estimates. The study goes on to find that the "*method shows less accuracy in months where the mean monthly temperature is close to the base temperature*" (p. 4).

It is important that the degree day period and meter reading period correspond. Typically HDD are calculated on a monthly basis. Therefore it is important to take the readings at the same time on the same date each month rather than the first Monday in each month. This will accommodate different month durations. If for some reason the reading cannot be taken on the same date a correction needs to be applied.

A significant issue using degree day analysis in buildings with intermittent heating e.g. heated Monday to Friday during working hours only but off at the weekends. Degree days are calculated on a 24/7 cycle. This means that degree day analysis will not give an accurate representation of the heating energy consumption. This is not a problem for this study as the dwellings are occupied on a 24/7 basis.

2.15 Conclusion

This chapter presented a comprehensive review of previous research completed in the field of energy efficient upgrading in the residential sector. The review presents a broad discussion on the social housing occupants and the factors that may affect energy use in dwellings. This chapter has shown that dwelling energy consumption encompasses a complex interdependence of many quasi-steady state and highly dynamic conditions including building fabric, external climate and occupant activities. In many cases how each factor interacts is poorly understood. The review also critically examined the findings to identify the performance gap between real and predicted energy consumption.

There is no guarantee that there is a satisfactory return on investment without a detailed understanding of the energy consumption and the real economic effect of upgrading. Existing methodologies lack a formal evidenced based approach and rely on simplified models which use limited survey data. The review highlighted the performance gap with the Warm Front project and a number of more contemporary research projects where real energy saving were far less than the model predictions. Oreszczyn and Lowe (2010) believe that researchers and campaigners are partially responsible for claiming that serious energy reductions targets can be easily achievable as a result of overselling technologies to governments over the past few years. Summerfield and Lowe (2012 p. 395) argue that *"in a world of realpolitik policy-makers"* it is understandable that policy makers seek straightforward prediction of how a particular policy will yield a particular result often based on unqualified scientific evidence. This has often led to considerable over exaggerations about what can be achieved by upgrading.

The review highlights the importance of and opportunities gained by upgrading social housing. Social housing occupants tend to be at higher risk of fuel poverty than private householders. Private homeowners tend to be reluctant to invest in energy efficient upgrading because of the investment costs and when outcomes are unproven. Though not strictly public buildings the LA buildings are not dissimilar too much of the housing stock in Ireland and as such can act as exemplars to the private homeowners.

This literature review has shown that there is a lack of evidence based research to demonstrate energy use patterns and actual benefit of energy efficient upgrading in the residential sector. This is the area which will be researched in this study. Similarly, in addition to technical attributes there is a need to include occupant behaviour in the evaluation of upgrading to establish cost optimal and value for money investment. Again this will be an integral part of the study.

The following chapter describes a novel evidence-based multidisciplinary methodology that seeks to address the gap in knowledge highlighted in this chapter.

Chapter 3

3 Methodology

3.1 Introduction

This chapter describes the methodologies, techniques and validation processes used to collect the data to establish, characterise and understand whole household energy use consumption of occupants in social housing. The methodology chosen was primarily quantitative and this was followed up by a qualitative study which examined how human behaviour affected energy use using a combination of ethnography, phenomenology and semi-structured interviews.

According to Summerfield and Lowe (2012 p. 396) *"in the face of ambitious energy demand policy agendas top-down energy consumption modelling does not suffice"*. They go on to highlight that one of the fundamental challenges for energy research in buildings *"is a reinvigorated effort to obtaining and updating empirical data"* and there is a *"general lack of systematic data collection"*. Currently, there is a dearth of knowledge surrounding systematic evaluation of whole household energy consumption and energy use patterns. With current thinking there is now a growing appreciation of the importance of non-technical approaches. Schweber and Leiringer (2012) highlight that published research exploring non-technical dimensions of energy and buildings has increased over that past decade. They highlight studies of thermal comfort, occupant behaviour and occupant satisfaction. Rogers and Ryan (2001) state that communities need meaningful analytical tools which take stock of the human, environmental and economic resources as a means to evaluate progress toward a secure a sustainable future.

A number of research strategies were utilised in this research to complete the aims and objectives of the study. Based on the findings from the literature review, the study embraces a mixed method, multidisciplinary approach. A predominantly quantitative methodology has been adopted in order to gather the empirical data required for subsequent analysis to establish the effect of energy efficient upgrading. The study also undertakes a qualitative methodology to evaluate personal experiences as a result of the energy efficient upgrading of the housing in Kilkenny.

This chapter outlines the Three Phased methodology developed based on the findings of the literature review and embraces the principles of the 'Triple Bottom Line of Sustainability' concept, as illustrated in Figure 13. The Triple Bottom Line Framework was developed by John Elkington the 1990's as a measure of corporate performance and sustainability generally associated with business and accounting in particular.

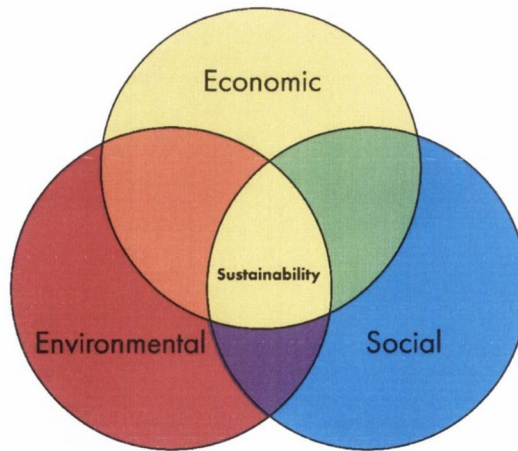


Figure 13 Triple Bottom Line of Sustainability

The framework is often referred to as the three P's: People, Planet and Profit, or the 'Three Pillars of Sustainability'. The framework has gained popularity with the public sector as a means to inform policy and evaluate their performance a full societal context. Slaper and Hall (2011 p. 7) state that *"policy-makers want to know the cause and effect relationship between actions—projects or policies—and whether the results move society toward or away from sustainability"*. Currently there is no definitive methodology to calculate the Triple Bottom Line (TBL) or measure of proportionally between each of the three categories. Thus organizations generally apply their own framework in a manner that best suits their own needs. Section 2.5 outlined that the majority of research in the past has been concentrated around technical aspect of energy use the building fabric and services and systems in relation to climate. A number of researchers identified this as limiting and identified the requirement to take the occupant into account.

There has been a recent increase in the number of mixed mode qualitative and quantitative approaches around energy use in buildings. These tend to investigate at only a small number of variables or take place over short periods of time (Pilkington *et al.*, 2011, Tweed, 2013, Barron and Sinnott, 2013). This is understandable due to the large cost and time constraints usually imposed. Therefore the researcher is particularly keen to deal with this limitation and was prepared to conduct the research over an extended timeframe. The end result was a longitudinal study incorporating 36 months of data collection.

As the concepts of reliability and validity cannot be supported statistically in qualitative research, *'within method triangulation'* was an important aspect of this mixed method research. This involved systematically evaluating data gathered with monitored and surveyed data, as shown in Figure 14. The aimed outcome was to give a robust, colourful and informative account of the energy use behaviour.

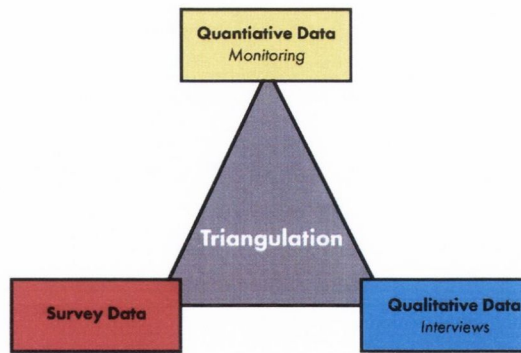


Figure 14 Triangulation Approach

The findings of the study from the data analysis showed that there was significant differences energy use between dwellings. The researcher felt it important to understand why energy usage varied across broadly similar houses. The triangulation that was employed aimed to fill in the gaps in knowledge surrounding the quantitative results. Many researchers talk about the requirement for triangulation in qualitative research to validate the data. Thomas (2011 p. 68) for example has described this as “almost an essential prerequisite” this type of research. Therefore, the researcher was keen to employ triangulation techniques.

3.2 Phase 1 Fieldwork - Survey Data Collection

3.2.1 Introduction

This section outlines two standard methodologies adopted to gather quantitative physical data that influences the energy performance of domestic buildings. The qualitative Phase Three data collection is dealt with in detail in Section 3.4. Survey data was also gathered during Phase Three of the study.

The Department of the Environment, Community and Local Government allocates capital funding to LA's through the Social Housing Investment Programme (SHIP) to improve the standard and quality of their stock. The level of funding allocated to increase energy efficiency is based on verified energy savings made by improving the buildings fabric and installing high-efficiency condensing boilers. Savings are verified by assessing the improvement in modelled energy performance of the dwelling from the results of pre- and post- upgrading Dwelling Energy Assessment Procedure (DEAP) calculated Building Energy Ratings (BER's). The procedure makes standard assumptions of occupancy rates, heating and electrical usage and behaviour. Therefore, this process assesses the building independently of the occupant variables. In line with the overall aim of the study and objective 3 the results were used to assess the accuracy of the model when compared with real energy use as presented in Section 6.2.

Infiltration is often seen as a part of the overall ventilation strategy in naturally ventilated dwellings and, until recently, little consideration has been given to improving airtightness when upgrading or altering a dwellings fabric. However, as fabric insulation requirements and assessment methodologies improve it is evident that more attention needs to be paid to the real effect of infiltration on overall building energy use. Therefore, enhanced characterization of real building performance is essential to develop prediction models and measure real energy reduction in buildings and building systems. For these reasons, understanding airtightness is important for new design and energy efficient upgrading of existing buildings. Mandatory airtightness testing was first introduced for new dwellings in Ireland in 2008. At that time, the reasonable upper limit for air permeability was set at $10\text{m}^3/\text{hr}/\text{m}^2$. This limit was revised down to the current upper limit of $7\text{ m}^3/\text{hr}/\text{m}^2$ (DEHLG, 2011, DEHLG, 2008). However, airtightness testing is still not required when upgrading existing dwellings.

BER's were completed in each of the houses in line with the requirement of SHIP. Using DEAP software as a design tool the results of the pre- upgrading BER's were used as baseline templates from which upgrading strategies were developed. The results were used to establish expected energy savings as a result of the upgrading. Standard blower tests were carried out on each dwelling pre- and post- upgrading primarily to reveal the effect of upgrading on dwelling airtightness and also to establish the real energy consumption related to infiltration in the dwellings.

3.2.2 Rationale for BER

Ireland has adopted the DEAP as the official methodology for calculating the energy performance of buildings in compliance with the European Directive 2002/91/EC and recast Directive 2010/31/EU. DEAP is a standardised compliance assessment tool for Part L 2005, 2008 and 2011 of the building regulations.

DEAP calculates a monthly energy balance and related CO_2 emissions under 'standardised' operating conditions for the provision of space heating, water heating, ventilation and lighting. The dwelling rating is independent of geographical location climate variations and effects of occupant behaviour. This includes assuming that lighting levels are the same in all dwellings, the number of occupants and hot water demand is correlated with floor area, all dwelling internal temperature profiles are the same and there is a fixed heating season from October to May inclusive (SEAI, 2012a, SEAI, 2012d).

To establish the energy performance of the building, the methodology utilises factors related to (SEAI, 2012a):

- Size, geometry and exposure;
- Construction materials;
- Thermal insulation properties of the building fabric elements;
- Dwelling ventilation characteristics and ventilation equipment;
- Heating system(s) efficiency, responsiveness and control characteristics;
- Solar gains through glazed openings;
- Thermal storage (mass) capacity of the dwelling;
- Fuels used to provide space and water heating (SWH) , ventilation and lighting;
- Renewable and alternative energy generation technologies

Thus, the results are independent of household size and energy use patterns offering only an estimate of real energy use of the building. In reality, the procedures are over simplified for the accurate evaluation of energy use but acts as a good reference point from which to guide the research.

3.2.3 BER Survey Aims

DEAP fulfils a number of criteria for gathering data for the study. The initial purpose was to carry out a detailed survey of the dwelling fabric, heating system and other building parameters related to energy performance to be used to establish a base line energy performance. The expected energy performance was used to compare the dwellings on a like for like basis. DEAP was then used as a design tool to specific suitable upgrading measures. Energy savings as a result of the upgrading were then used to establish compliance with the requirements of SHIP. The results generated as part of the survey were used in the triangulation process and compared with the monitored energy use and qualitative data.

3.2.4 BER Survey Methodology

Standard BER's were done on each dwelling pre- and post- the upgrading process. The prescribed procedure for Building Energy Rating was followed using the standard DEAP software and manual:

- 2008 EDITION, VERSION 3.0 for the pre- upgrading surveys; and
- 2012 EDITION VERSION 3.2.1 for the post- upgrading surveys.

The information required to populate the software was sourced in accordance with the relevant version of the DEAP manual (SEI, 2008a, SEAI, 2012a). The surveys were carried out in accordance with Dwelling Energy Assessment Procedure (DEAP) Survey Guide - VERSION 2.1 (SEAI, 2012c).

The guide sets out the supporting data or evidence required to complete the BER. To ensure accurate representation the buildings characteristics the guide sets out the procedure for gathering data including:

- External Survey;
- Internal Survey;
- Dwelling Sketches and Drawings;
- Room by Room Survey; and
- Attic Space Survey.

The guide makes particular reference to the default values in Appendix S - DEAP for existing dwellings: survey methodology and default data. This section of the DEAP manual, (SEAI, 2012a), was particularly pertinent for this study as a number of non-default values were not available. Each time a BER was done Appendix I: DEAP Survey Form from the DEAP manual was completed. In addition the researcher took an extensive array of photographs as proof of the works.

3.2.5 Rationale for Airtightness Testing

The location of individual air-leakage paths are often difficult to identify by visual inspection, thus, assessing the building envelope as a whole, using the standardised blower door test, is the only reliable means of assessing building airtightness. Evaluating airtightness usually refers to measuring the flow Q (m^3/s) through the building envelope as a function of the pressure differential P (Pa) across the building envelope.

The test quantifies the airflow through the building envelope as a function of the induced pressure differential and utilizes the power-law relationship, as shown in Equation 9, to describe and validate low pressure building envelope leakage (Sherman, 1987, Walker *et al.*, 1998, ATTMA, 2010).

$$Q = C \Delta P^n \tag{Equation 9}$$

where:

- Q_{50} is the leakage air volume flow rate in (m^3/hr);
- C the flow coefficient that is related to the size of the opening;
- ΔP the internal/external pressure difference across the envelope, Pa; and
- n the flow exponent characterizing the flow regime.

DEAP uses q_{50} (Q_{50} divided by floor area) to estimate air infiltration under normal conditions. This model is crude and simply scales infiltration linearly which Sherman (Sherman, 1987) says ignores “physical principles at work”.

3.2.6 Airtightness Survey Aims

The pre- and post- upgrading airtightness tests provide real airtightness parameters for standard construction Irish dwellings. The testing revealed the effect of energy efficient upgrading on airtightness. The results are used to calculate infiltration under normal conditions and establish associated heat loss taking climate variables into account.

3.2.7 Airtightness Survey Methodology

Testing was carried out in accordance with the Air Tightness Testing and Measurement Association) Technical Standard (ATTMA, 2007, ATTMA, 2010). The Technical Standard is generally compliant with IS EN 13829:2001 Thermal performance of buildings – Determination of air permeability of buildings – Fan pressurization method. Evaluating airtightness usually refers to measuring the flow Q (m^3/s) through the building envelope as a function of the pressure differential P (Pa) across the building envelope. The standard blower door test measures this flow at a steady 50Pa pressure difference, effectively negating the effects of buoyancy and wind (Etheridge, 2011). Due to the variety of methods used to deal with intentional openings during testing, direct comparison of blower door test results between countries is often difficult (Carrié and Rosenthal, 2008, Caillou and Van Orshoven, 2010). Thus, clarity in defining the test procedure is important. Testing to determine the air permeability was largely compliant with Method B, of EN 13829. External doors and windows, intentional vents, attic hatches, letterbox and extract fans were closed but not sealed; open fireplaces were sealed. Prior to testing, dwellings were surveyed and the internal envelope area (AE) and volume (V) accurately calculated.

The Retrotec Q46 Automated Blower-Door apparatus used for testing has a Maximum Flow at 50 Pascal test pressure of $9,514\text{m}^3/\text{h}$ and Minimum Flow at 10 Pascal of $65\text{m}^3/\text{h}$ and incorporates regulated variable frequency speed controllers to provide a stable speed control, making it suitable for testing dwellings. The fan was secured to the house front door using the Retrotec soft panel frame. Pressure and flow rate were controlled using a laptop, connected to a DM-2A Automatic Micro-manometer, which controlled the fan. In addition to the DM-2 the 'Fantestic' software continuously logged a number of parameters including fan flow, test pressure, airflow exponent and gave a variety of results based on physical input parameters.

Stephen (1998) found that pressurization and depressurization results can vary by up to 20%. The 'valve effect' can also occur where by a component can be pushed up during pressurisation and pulled down generating a seal during depressurisation. Hence, to mitigate the 'valve effect' and other directional aerodynamic characteristics pressurization and depressurization test cycles were

completed. The average of both results was recorded as the air permeability for the building. During testing, wind speed and ambient temperature conditions were measured using a hand held thermo-anemometer to ensure compliance with IS EN 13829:2001.

The software can present the results in a number of ways. Normalised air permeability characteristics are usually expressed as:

- Air Permeability, q_{50} , - measured as the volume of air passing through each square metre of building envelope, including ground floor area, in one hour ($\text{m}^3/\text{hr}/\text{m}^2$). This should not be confused with Air Leakage Index which has the same units ($\text{m}^3/\text{hr}/\text{m}^2$) but excludes ground area;
- Air Leakage Rate, n_{50} , – air flow rate at a reference envelope pressure difference by the gross internal volume of the dwelling. Unit: air changes per hour (ach).

In line with Part L of the Building regulations Air Permeability was used as a measure of the dwelling airtightness.

During testing in-depth visual and smoke pencil tests were carried out. Air leakage paths identified by the smoke pencil test and simple observations were similar to those identified in previous research (Sinnott and Dyer, 2012, EST, 2005, Sherman and Chan, 2003, Jaggs and Scivyer, 2006b).

The data gathered from through the DEAP and airtightness testing process was used throughout the study as one part of the triangulation process. As discussed in detail in Chapter4, Waterford City offered the opportunity to carry out a preliminary study where BER's and airtightness testing were carried out on 28 single family homes.

3.2.8 Limitations

The DEAP survey is a useful methodology for gathering detailed physical information related to energy performance of dwellings. The procedure predominantly uses quasi-steady state calculations and makes a number of standardised assumptions to estimate annual energy usage and associated CO₂ emissions. This allows like for like comparison of dwellings. Such comparison may be useful for people wishing to rent or buy a property methodology but it does not accurately reflect or predict the real energy performance of the dwelling. This makes it impossible to establish energy use patterns and the actual benefits of upgrading.

Airtightness testing is a simple mechanism to establish infiltration at a large pressure differential across the envelope. However, this physical measurement does not reflect infiltration under normal working conditions. DEAP uses a simplified methodology to estimate infiltration using blower door test results. This does not take account of the many factors that affect real infiltration rates. There is a need to improve this model to more accurately predict heat loss due to infiltration that increases the level of accuracy but also retains a level of calculation simplicity for the user. This is further addressed in Chapter 7.

3.3 Phase 2 Fieldwork - Monitoring Data Collection

3.3.1 Introduction

Bi-Monthly utility bills are typically the only source of measured data regarding the energy consumption of most dwellings as the widespread roll out of smart metering still is still in the pipeline. These bills are often estimates with meters being read on average three times per year in Ireland. This means that using utility bill data is insufficient as large disparity on hourly or daily patterns cannot be identified from this data. This was identified by (Majcen *et al.*, 2013) who used data from the calendar year 2010 but states that because the meters in the Netherlands and physically checked every three years it is possible that the consumption data used in the study are not the actual data for 2009, but contain some averages from the years 2006 - 2009.

Consequently, to evaluate the real benefit of energy efficient upgrading in a dwelling it is necessary to determine a baseline of actual energy use pre- intervention. Measurement requires information about the building, which is dynamic in nature. External climate has an impact on energy use owing to the nature of energy use in domestic buildings. Data needed to be gathered over an extended period of time to establish this baseline energy use. This allows for analysis of any external parameters that affect the energy use particularly local climate.

3.3.2 Rationale for methodology

It is clear that DEAP only gives an estimate of dwelling energy performance which is independent of specific climate and occupant characteristics. This section describes the development of the methodology whereby quantitative real data relating to the whole house could be gathered. An important feature of the study was to isolate the actual effect of physical upgrading from potential changes in occupant behaviour. It has been argued that in experimental observation and measurement both conscious and unconscious bias becomes a real possibility when humans are aware that they are being observed as a focus for research. This may manifest itself with the person acting differently than normal and alter their behaviour to take into account the purposes of the research. Often referred to as the 'halo effect' it can be overcome by making covert

observations (Nisbett and Wilson, 1977, Denscombe, 2003, Robins *et al.*, 1996). Covert implies that the occupants were being observed without their knowledge, this was not the case. The occupants were aware of the research and it was hoped that because they didn't physically see the researcher they were therefore less likely to change their normal behaviour. Thus, remote monitoring and minimal contact with the dwelling occupants was considered an integral part of the research. It was important to design a wireless system to minimise aesthetic impact and increase speed of installation for the occupants.

3.3.3 Aim

The aim was to develop a low cost, self-contained, accurate and precise remote data acquisition system suitable for the domestic sector energy monitoring. The system requirements were to locally log gas and electricity usage, indoor temperature, humidity, air quality and external environmental conditions every 15 minutes in each house and then transmit the data remotely to a secure database for subsequent analysis for at least one year pre- and one year post- upgrading.

Thus, in a research context, the information gained was key to:

- Establish the real energy savings as a result of the energy efficient upgrading;
- Assess the energy use patterns;
- Compare the data with modelled data from DEAP;
- Provide data that could be used to establish the real return on investment.

3.3.4 Objectives

There were a number of key objectives for this section of the study. These are now listed in a random order:

- Appraise and select the best communication protocol for transfer and storage of data within the buildings and to the central hub;
- Develop devices to acquire the buildings energy and environmental parameters shown in Figure 15;
- Develop the best system to remotely transfer the acquired data to the server;
- Ensure the system could work autonomously, had a good battery life, was discrete with minimum aesthetic impact;
- Design a system that could be easily scaled in terms of individual dwellings and multiple dwellings.

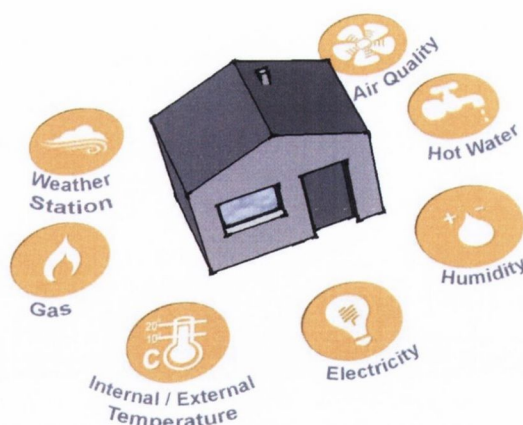


Figure 15 Monitored Energy and Environmental Parameters

3.3.5 Monitoring Methodology – Bespoke Energy Monitoring and Reporting System

A review of the best ‘off the shelf’ systems to remotely monitor all the parameters required for the study failed to yield a result. There are an assortment of individual energy and environmental monitoring sensors and systems on the market. However, no one system could provide a whole house monitoring solution as required by this research. In addition, many current systems are aimed at the commercial sector and are prohibitively expensive. Each individual system has its own communication protocol. Many of these individual protocols were company protected, which prevents the easy integration of additional sensors or components. A particular difficulty arose when attempting to monitor the in-situ gas meters because they did not have pulse outputs. Therefore, the development and deployment of a novel bespoke system was required to undertake the study. Following a selection process VVS Technology was procured to provide the technical development support for the system design to meet the specification requirements of the project.

Database and Website

The requirement of the system was to reliably collect data and distribute it to a server for presentation on a simple web based user interface accessible through the internet. The server required multiple redundancy, regular data backup and be on a hardened Internet connection which could be protected against Denial of Service (DOS) attacks.

The preferred option was to buy (hire) a cluster of servers from a server farm. VVS Technologies favoured supplier had a clustered farm with dynamic load balancing, automatic backup on site and UPS with site generator standby for 30 days.

A cluster of five servers are employed to process the data. In the case of any attack or malfunction on one server back-up servers act to protect the data. All firewalls are setup to handle considerable Internet traffic from a secure, multiple redundant set of Internet pipes. It was decided to make the entire site “read only” to increase data security and all interactions on an MD5# encryption were presented as a PHP script on the website as shown in Figure 16 . This choice gave the option to develop a user friendly dashboard in the future. VVS Technology undertook to complete basic cleaning of the data by removing extreme values in SQL. In total 13000 pieces of data were recorded every day, growing the database by 1.2 megabytes in 24 hours.

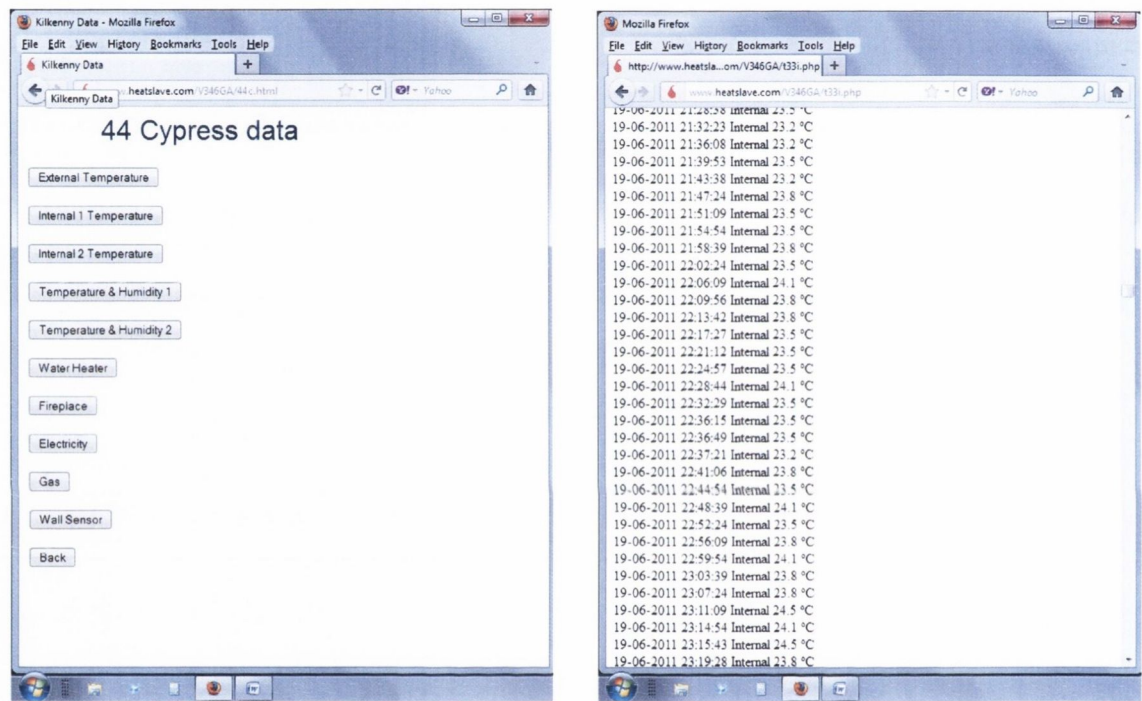


Figure 16 Typical Website Presentation

Data Transfer

Pre- upgrade surveys revealed that very few households had broadband availability. Those that did were of plug in dongle style connections with limited use and reliability. This posed the challenge of transferring the data from the dwellings to the data base. In Ireland, a 1Mb broadband connection costs approximately €250 per annum per connection. The option to use a GSM system, where a SIM card is installed as part of the system was evaluated as an alternative. However, cost and potential reliability issues of the system made this unattractive.

Therefore, a bespoke system was designed utilising the proximity of the houses in each estate. As demonstrated in Figure 17 each estate has a hub, being one designated building, with broadband connection from where the data is transferred to the database. All dwellings were within a radius of 600m of their local hub. A local WiFi was established whereby the Data Concentrator (DC) in each house is connected to the hub by secured WAP bridges and Antennas, as shown in Figure 18. This significantly reduced the cost of the project, requiring just two broadband connections. Scalability of the system is very simple whereby additional dwellings can simply be added until the broadband capacity is exceeded.

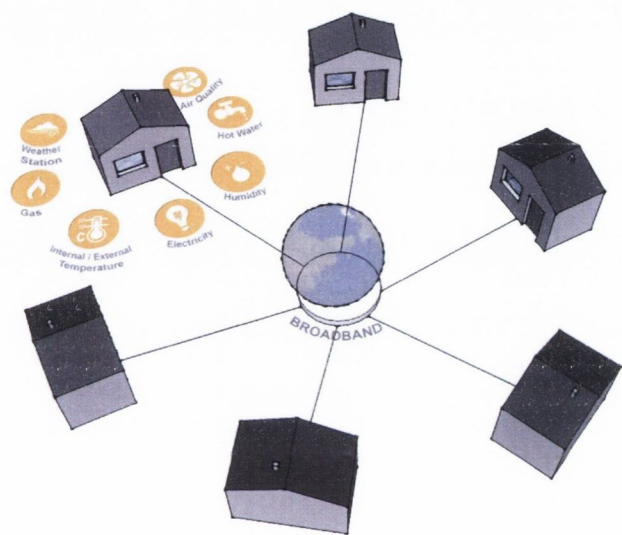


Figure 17 Data transfer from dwelling to hub to database



Figure 18 WAP connection located on the roof of each house to ensure visible line to antenna

As shown schematically in Figure 19, the essence of the system is to collect data within the house, transfer the data to a hub, which in turn sends the time stamped raw data to a database, where formatting is carried out for presentation on a website.

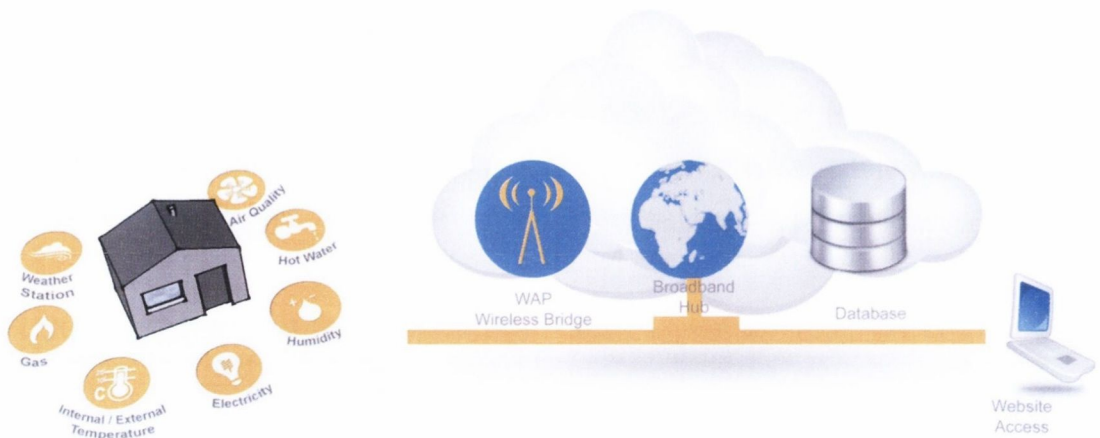


Figure 19 Data Collection and Transfer to Database

Internal Data Acquisition

The integrated communication of a number of components was critical to data gathering within the dwellings, as the following details.

Data Concentrator (DC)

A local WiFi was configured with one property in each location having a broadband connection and each DC connected to the broadband router by secured bridges. The router was configured to give DHCP (Dynamic Host Control Protocol) so a DC on power up asks for and is leased a local IP address. The router translates the local IP of each DC to the public or proxy IP of the router Network Address Translation (NAT) and directs traffic in both directions to the appropriate device.

Located in the attic of each house, these powered units and are key to the collection of data. The DC performs three functions acting as:

- an IP client to the server, making a connection and uploading and downloading the data;
- a data storage unit to store data from the sensors if the data connection to the hub is slow, none existent or unavailable for some reason;
- a coordinator for the wireless network of the sensors.

The DC does no processing of the data other than packaging it up for IP and doing an MD5# encryption. Each raw data packet is stored in a circular buffer, giving around 21 days of data storage. All data is time stamped.

There is a time index on each slot although the “real time” of a data package is time stamped when it has been correctly sent to the server, adjusted by the index.

Around each DC there is a wireless network of battery powered sensors. Three approaches to getting the information from the sensors to the networks were evaluated:

1. a “design it yourself” and do all the bi-directional wireless transmitters and receivers on a permitted frequency;
2. ZigBee, an international free open standard offering a low entry cost and easy access to hardware;
3. Zwave; a similar setup to ZigBee but a noticeable different approach required for development. Zwave is a proprietary system requiring a license to use from Sigma Designs. All Zwave devices work with each other. They work on a lower frequency than ZigBee so better range for the same power but antennas are physically larger. The European and US frequencies are different so devices incompatible.

The cost of both the Zwave and self-designed systems were found to be prohibitively expensive to implement; therefore, a Zigbee system was adopted. Zigbee is a low-powered radio communication protocol most suitable for applications that require low data rates and low power consumption. ZigBee operates on the 2.4GHz radio band and can use channels 1 to 26, if permitted. A personal area network (PAN) is created allowing ZigBee enabled nodes to transmit data either directly to the PAN coordinator i.e. the DC in the house or alternatively uses other nodes as a “hop point” to the DC, forming a mesh network. For this study each house has a unique DC PAN co-ordinator, as shown in Figure 20, and the maximum number of end points was restricted to 10. This low power consumption system offers the project the option of long battery life; necessary for the two year project duration.



a)



b)

Figure 20 (a) Data Concentrator (DC) and (b) Personal Area Network (PAN) Hardware

ZigBee is designed for short distance transmission up to 30m or 100m line of sight depending on power output and environmental characteristics. Distance can be transmitted over longer distance by passing through a range extender or strategic use of the mesh network.

On first power up the DC PAN co-ordinator scans all permitted channels; in Ireland this is channels 11 to 26 inclusive. It tests for other PANs, WiFi modems etc. and selects the first channel with the lowest energy spectrum. This scan can take nearly 4 minutes but acts as the basic "Find a free Channel". If no free channel is found it elects the lowest usage channel. As an automatic correction to new channels blocking the selected channel, if no end point/node/sensor communicates for 60 minutes then the scan is started again.

While ZigBee has a lower entry cost, in terms of development and knowledge environments, there is a high probability that ZigBee devices from other manufacturers, while they won't interfere with each other, will be unable to communicate with each other. This posed a problem when introducing hardware like the Xemtec Comet requiring considerable development and testing.

Sensor configuration

The data transfer configuration was designed to be the same regardless the parameter that the sensor is measuring. This effectively allowed for a standard sensor Printed Circuit Board (PCB) and programme with the ability to plug in individual sensors. The sensors processor was configured to sleep for a minute, wake up and then decides if to take a measurement or not, transmit that measurement or not or return straight to sleep depending on what we are measuring the configuration changes. If the sensor was to act as a hopping device within the mesh from another sensor then it wakes 30 seconds earlier and stays awake listening for its hop link. As all processors sleep at the same rate then this scheme works with high reliability although at a slight power budget cost to the hop device.

A reading is taken at time zero for a perfect transaction. It is sent to the DC two milliseconds later and if this is a success it gets a valid receive from the DC. The DC establishes a socket to the server giving a total transfer time of less than 0.3 seconds from reading to being on the server.

However, there were a number of potential failure mechanisms identified in the system and best available solutions adopted:

- A reading is taken and sent via Zigbee. It has a route via a "hop" to another sensor. The worst case delay from the hop sensor getting data to that sensor taking its reading to it sending it to the DC will be 15 seconds plus the two milliseconds to the hop and two

milliseconds for hop to DC. In other words 15 seconds worst case or 4 milliseconds in addition best case. In this case the sensors lock in sync and the data from both sensors will arrive at the server with the same time stamp.

- If the PAN is not available, its changed frequency or radio interference prevents a connection the sensor will try three times each taking between 250 ms and 750 ms. If that fails the sensor pushes the reading into a FIFO (First in First out) stack. When the sensor next tries (15 minutes) and it connects then it sends the last reading first with a (subtract 15 minutes flag) first and then the new reading. The previous reading has about the right time plus or minus 10 seconds but took 15 minutes to arrive.
- If the sensor tries seven times and fails it tries a new scan of channels to find the PAN. It then empties its stack which now contains seven readings. The first missed one is two hours late. It is timed stamped about right as each slot in the stack is minus 15 minutes.
- If a sensor fails to connect with the Data Concentrator (DC) it will try again twice more. If that fails the sensor pushes the reading into a FIFO (First in First out) stack. When the sensor next tries, 15 minutes later, and it connects then it sends the last reading first, with a subtract 15 minutes flag, and then the new reading. Each sensor has a 1 megabit flash card, so as each reading is 100 bytes, the card can store 13 days' worth of data at 15 minute intervals.
- The DC sends a ZigBee beacon on the selected channel. On first power up an endpoint scans all permitted channels looking for a beacon. When it finds one it connects to the PAN and transmits its long and short addresses. The Co-ordinator accepts the connection and path from endpoint to itself. If the signal it has 'hopped' a virtual circuit path is established.
- Each ZigBee device has a long and short unique address. Each PAN has a number as well. This allows an endpoint to be a member of more than one PAN but connect to a PAN co-ordinator via other endpoints if required. This means there is a high probability that ZigBee devices from other manufacturers, while they won't interfere with each other, will be unable to communicate with each other.
- Each time a sensor wants to send data it uses the virtual circuit established earlier. If this circuit fails too often, set at 7 for this research, the endpoint re-establishes a connection and as it has the same long and short address the co-ordinator updates the path table. Diagnostics are imbedded in the co-ordinator and endpoints, included in the network packets and stored on the server. This allows engineering to analyse the PAN for problems.

Temperature, Humidity and Air Quality

The temperature sensors were standard VVS Technology designed PCBs with an attached temperature sensor as shown in Figure 21. This connection was designed as a plug in for potential interchangeability of other sensors. The sensors are similar in size to a standard light switch. Internal temperatures were monitored in the hall, sitting room, kitchen and main bedroom. Sensor placement was critical to avoid draughts, convective currents and other heat sources that would distort readings. Placement also had to take account of the occupant's wishes and typically tried to be out of view about 1.7m above ground level. This was not always possible.

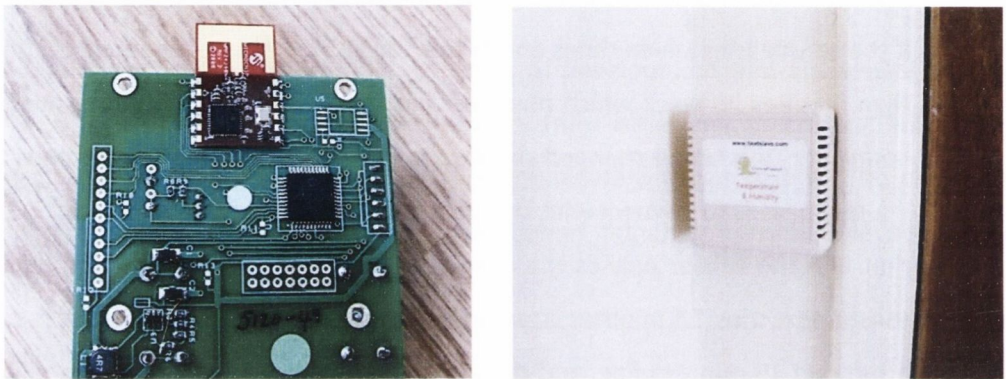


Figure 21 PCB with temperature sensor protruding from the top and typical room mounting

Condensation is often reported as dampness to KCC housing department. Temperature sensors have integrated humidity sensors in the kitchen and main bedroom to monitor potential increased humidity as a result of fabric upgrading. Temperature sensors report in degrees Celsius with a reported accuracy of $\pm 0.5^{\circ}\text{C}$. Percentage relative humidity (% RH) was measured with a reported accuracy of $\pm 3\%$.

Air Quality monitors were installed in four houses. The FIGARO TGS 2600 and TGS 2602 sensor heads monitor per million (ppm) of carbon monoxide, methane and Iso-butane present in the air. The aim is to establish if upgrading effects indoor air quality.

Electricity monitoring

The cost of monitoring each individual electricity consuming appliance in each dwelling was beyond the scope of the project. A compromise was to monitor individual circuits along with the main incomer at the distribution box. VVS Technology developed a 6 channel electricity meter again consisting of the standard PCB with 6 plugins. This is fitted beside the electrical distribution box electricity and connected using clamp-on current transformers (CT's) to incoming mains and up to five other circuits as shown in Figure 22 a and b. This allows for the monitoring of sockets, shower, lights, immersion heater and electric cooker if installed. The units were calibrated and

checked against the meter box reading. Data is presented on the website in kilowatt hours (kWh). When installing the CT's a number of unplanned distribution board replacements had to be undertaken due to the poor condition of the existing boxes as shown in Figure 22c.

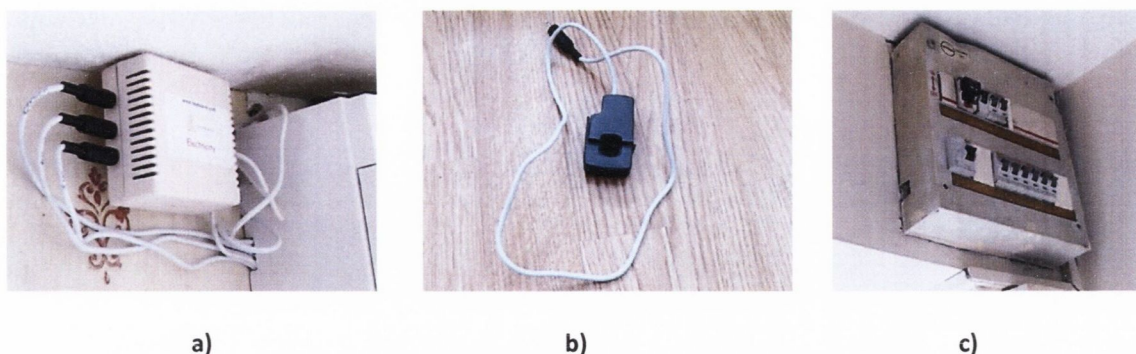


Figure 22 Typical Circuit Board, 6 Channel Electricity Meter and 10Amp CT

Gas metering

The residential natural gas supply network is provided by Bord Gáis in Ireland. Bord Gáis used Elster BK-G4 residential diaphragm meters as standard until recent years, as shown in Figure 23a. The meter is specifically designed for domestic applications and has an analogue index that must be read manually. These older Elster BK-G4 meters do not have a low frequency (LF) pulse output as standard, which is the simplest method to attach a monitoring system.

A number of practical options were extensively evaluated in cooperation with technical representatives from Bord Gáis including:

1. Join the Bord Gáis smart metering programme and receive the monitored data from Bord Gáis;
2. Install a LF pulser, which the gas meter manufacturers offer as an add-on, to the existing meters. The output module is accurate to 0.01m^3 ;
3. Replace the existing meters with a modern meter incorporating a pulser;
4. Break the mains and install an inline meter with pulse output;
5. Install an ultrasonic meter.

At the time of developing this research, the Smart Metering Programme was closed to new entrants. In addition, Bord Gáis technical representatives expressed concern about sharing information gathered as part of the scheme. Though technically possible Bord Gáis could not allow alteration works to their meters to fit an LF pulser by a third party. Quotations from Bord Gáis and time delay implications to the project to replace the meters were found to be prohibitive to the project.

Following a consultation period with Bord Gáis, permission was granted to undertake either of two possible solutions:

1. Carry out whatever works on the customer side as desired.

Three options to fit downstream meters were reviewed in detail:

- i) Fit a second standard new Elster meter with pulse output;
- ii) Break the main and fit in inline flow meter with a pulse output;
- iii) Fit an ultrasonic flow meter with a pulse output.

The cost, time requirement and disruption to the occupants meant that none of these options were deemed viable for the study.

2. Without interfering with the meter, fit a galvanic isolated unit to optically read the meter. At the time very few optical meter readers (OMR) were commercially available. Since the commencement of the project this has changed substantially. The OMR chosen was a wireless battery powered Xemtec Comet XRS – 60 optical reader, as shown in Figure 23b. This galvanically isolated reader clips to the front of the meter and captures meter data optically; processes the data locally with the front end chip called Opto-ASIC, converts to digital format and transmits the data over any communication network. Battery life was expected at 5 years. For this project a large amount of development work was undertaken by VVS technology to integrate the technology into their system.



a)



b)

Figure 23 a) Standard Elster BK-G4 meter b) Xemtec Optical Gas Meter

Water Heating

To establish an estimate of the proportion of heat energy provided for SWH, a wireless temperature sensor is fitted on the flow and return pipes of the hot water tank of each house as shown in Figure 24a and b. The sensor consisted of a thermocouple attached to the flow and return pipe to measure the temperature differential (ΔT) and volume of water could be used to establish approximate hot water usage.

External Environment

Weather stations were erected at each site gathering temperature, wind speed and direction as shown in Figure 24. These have their own IP address and are connected directly to the broadband routers. They transmit their data every 20 seconds directly to the server.

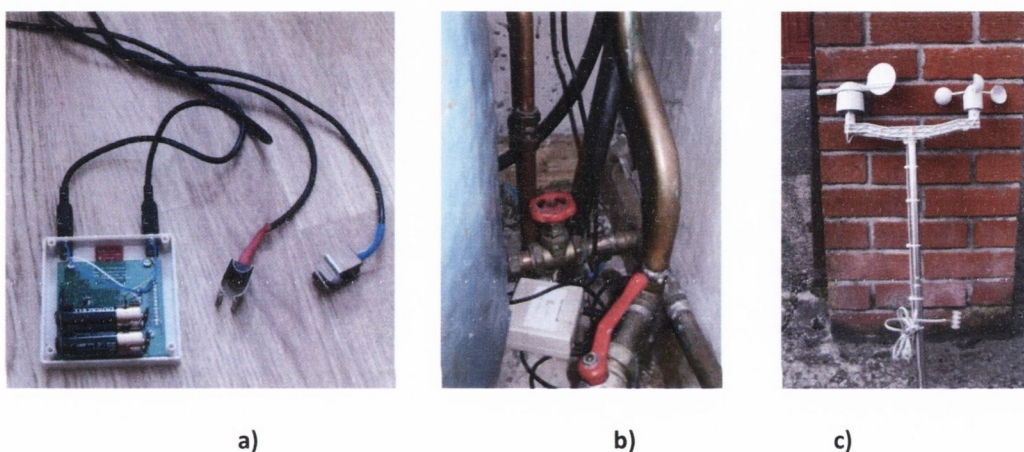


Figure 24 a) PCB with Thermocouples b) Sensor in-situ c) Weather Station

Solid Fuel

Camilleri *et al.*, (2007) identified a number of intrinsic barriers to gaining accurate solid fuel usage in dwellings. The study found in situ efficiency calibrations were time consuming, expensive and contained too many uncertainties to be accurate. Also, fuel usage log book accuracy was not as good as hoped. For the purpose of this study, asking occupants to fill out fuel logs or weigh their fuel use was believed to be at odds with a fundamental objective of the study to minimise interaction with the occupants. To establish an estimate of solid fuel use a wireless temperature sensor was positioned above each fireplace to monitor when the fire was in use. Occupants were asked to keep a record of their monthly fuel use. This data was gathered as part of Phase three of the study.

3.3.6 Limitations

It was prohibitively expensive for this study to capture every energy user and virtually impossible to monitor all environmental parameters that affect energy consumption and occupant comfort in the dwellings. Options explored were to do more monitoring on fewer dwellings or more dwellings with less depth of monitoring. The scale of monitoring had to be tailored to suit the budget as well as provide enough detail to establish quality information. For future studies the mesh system allows for the simple addition of sensors.

Though the intention was to monitor the energy use without affecting behaviour the simple act of surveying and installing energy monitoring has to have an effect on energy use. This should be negated somewhat by the duration of the study.

There was a time limitation whereby the equipment had to be installed before the heating season began. Otherwise the study would not monitor a complete heating season or would have to be postponed for a year. This put a lot of pressure on the development programme and on-site installation. Not all equipment was installed at the same time which meant over a period of approximately a month required repeated visits to each dwelling.

Fundamentally the system can monitor when, where and how much energy is being consumed in the dwellings but cannot answer the question – *why*? This limitation is addressed as part of the triangulation process in Phase Three of this study.

3.4 Phase Three Fieldwork: Interview Stage Methodology

3.4.1 Introduction

This section outlines the methodology used to gain an understanding of the principles and perspectives of *how* and *why* occupant behaviour affects energy use. Occupant behaviour has been identified a significant contributor to the gap between actual and predicated energy performance of buildings (Haas *et al.*, 1998, Haas and Biermayr, 2000, Sunikka-Blank and Galvin, 2012). This section outlines the qualitative research methods and instruments used in Phase three of the research study. The main aim of the this part of the research was to explore in depth a number of questions generated by the analysis of the data gathered through the phase one and two quantitative study. This section sets out the methodology used to understanding the rationale behind the quantitatively analysed energy use by including to variable of human behaviour into the matrix.

The aim of the section of the research study is not seek to unpick the nuances of human behaviour but to investigate the beliefs, perceptions, attitudes and energy use behaviour.

Cresswell states that:

Qualitative research is an enquiry process of understanding based on distinct methodological traditions of inquiry that explore a social or human problem. The researcher builds a complex, holistic picture, analyses words, reports detailed views of informants and conducts the study in a natural setting.

Cresswell (1998 p. 15).

Schweber and Leiringer (2012) conducted an extensive but not exhaustive literature review of published non-technical research relating to energy and buildings. The review revealed that positivist methodologies have dominated. They found this to be the case even when qualitative data is being used. They further state that this type of research needs to embrace interpretivist approaches. Positivist methodologies apply a scientific orientation that focus on deriving facts from observable experience rather than intuition. Ritzer (1996 p. 284) *"Positivism accepts the idea that a single scientific method is applicable to all discipline"*. Positivists believe the observer can remain independent and human values are irrelevant because the world is perceived as external and inherently neutral. The intention of the interview analysis was to be as impartial and unbiased as possible. However, Grix (2010) and Hammersley and Atkinson (2007) believe that the researcher cannot remain detached, will have preconceptions, that ultimately impartial analysis is impossible and the researcher should not pretend otherwise. The researcher leaned towards an interpretivist approach as the literature showed that human behaviour is an important variable in energy usage.

This methodology involved aspects of an extensive range of qualitative methods of inquiry involving phenomenology, ethnomethodology, ethnography, case study analysis, interviews and observation in an attempt to understand how human behaviour interfaces with energy use. Ritzer (1996 p. 215) in a review of the work of Alfred Schutz (1899-1959) on Phenomenological Sociology says:

Much of Schutz's work focuses on an aspect of the social world called the life- world or the world of everyday life. This is an inter-subjective world in which people both create social reality and are constrained by the pre-existing social and cultural structures created by their predecessors.

Furthermore he states *"Schutz differentiated between intimate face to face relationships (we relations) and distant and impersonal relationships (they –relations)"*. Ethnomethodology was a theory espoused by Hilbert Garfinkel and is the study of the body of common sense, knowledge and the range and procedures and considerations (the methods) by which the ordinary members

of society make sense of, find their way about in and act on the circumstances in which they find themselves (Heritage, 2013 p. 4).

Researchers in this tradition are heavily tilted in the direction of the study of everyday life. While phenomenological sociologists tend to focus on what people think, ethnomethodologists are more concerned with what people do (Ritzer, 1996 p. 217). This research is concerned with the micro -orientation to actors and their actions and behaviours particularly as this impact on energy usage. Norbert Elias in his classic work 'The Civilizing Process' asserts that people do not make changes rationally. Their behaviour is more rooted in emotions than in rational considerations (Elias and Jephcott, 1982 p. 101 -104). Given the applied nature of the research this was the approach favoured by the researcher.

3.4.2 Research Approach and Design

This research uses survey-questionnaires, semi-structured interviews and observations combined to gain a holistic understanding on how occupant behaviour and perception affects their energy consumption. Interviews are one of the most common strategies for gathering qualitative data. Depending on the structure of the interview the interviewer can develop a relationship with the interviewee and utilise some ethnography and phenomenology. Schostak (2005 p. 10) describes an interview as:

individuals directing their attention towards each other with the purpose of opening up the possibility of gaining an insight into the experiences, concerns, interests, beliefs, values, knowledge and ways of seeing, thinking and acting of the other.

Interviews are commonly used to test a priori hypotheses. This usually takes the form of a structured interview with set questions. Unlike other forms of research which begin with a theory which is then verified, this study takes a grounded theory approach with the intention of generating a hypothesis. This approach encourages the interviewee to develop a relationship with the interviewer allowing freely flow of information. This allows the interviewer to later interpret and analyse the data. The purpose of this approach was to contribute to the body of knowledge by formalising the meaning that the occupants' perceptions and life experience meaning energy. The researcher comes from a strong technical background so it was particularly important to try and understand how the occupants being interviewed understood and apply their knowledge of energy usage.

3.4.3 The Interview Aim

The research attempts to portray the reality of energy use behaviour and experiences and give a voice to their views of dwelling occupants and qualify gaps in knowledge raised in Phase 1 and 2. The ultimate goal was to research *with* the occupants rather than just about them.

3.4.4 Interview Methodology

The overall aim of the study was to evaluate the effect of the energy efficient upgrading. Therefore, it was prudent to conduct two interviews, one pre- and one post- the upgrading works. It was deemed important to conduct the interviews in a reasonable time period time after the installation of the monitoring equipment and before any upgrading works commenced so as to minimize influencing their answers. The first interview took place almost one year after the monitoring programme commenced over the summer period following the first winters energy monitoring. The second interview took place in the first summer after the upgrading, again following a heating seasons monitoring.

The interviews took place in the interviewees' homes where they would feel most comfortable, at a time that was convenient to them. All adult occupants were interviewed. Interviews were conducted in either the sitting room or the kitchen. Prior to taking part in the interviews the interviewees were talked through and asked to sign a consent form (see Appendix C). To relax the interviewees and to gain their trust, the householders were reassured that they were under no obligation to answer any questions. The interviews were semi-structured which allowed for both free flow conversation but also the collection of some quantitative data. Thus each interviewee was asked the same questions but the researcher could explore and probe further on any interesting points as they arose.

Pre- Upgrading Interview

The purpose of the first interview was to establish occupants' perspectives on their standard of living, there awareness of their energy consumption. An extensive combined survey sheet and questionnaire was designed to gather as much quantitative data as possible and loosely guide the conversational flow of the interview. The relevance of some of the questions was not obviously evident at the time of compiling the questionnaire. The purpose was to have a friendly conversation and also gather information that may lead the study in a different direction or perhaps be useful for future related studies. The detailed questionnaire, reproduced in Appendix D, was verbally administered during the semi-structured interview. Depending on the flow of the conversation not all the questions were addressed and quite often were not dealt with in the prescribed order of the questionnaire.

So rather than stifle the flow of conversation, different areas could have been covered but later the interviewer would go over question that would not have been discussed.

The interviews were recorded digitally. Minimal note taking was the norm in order to maintain eye contact and rapport with the interviewee. Questions were posed in an open ended manner with follow up prompts. This allowed for post interview, quantitative and interpretative phenomenological analysis to be carried out. Each of the nine interviews took between one hour and one hour twenty minutes to complete. The interviews often migrated down long and winding paths of occupant's personal circumstance, comfort and lifestyle relationship with money and energy bills, and the realisation as they spoke and how their lifestyle effects energy usage. Where feasible the interviewer allowed the interviewee to dictate the flow of the interview once all the relevant areas were discussed. Though this was time consuming, it was felt important to allow the occupants to talk at length so that they would be relaxed and it would also develop the rapport with the researcher

The interviews covered a number of themes/elements, including:-

- Building Parameters:- similar to survey in Section 3.2, but also included dwelling quality, cleanliness, maintenance, urban density and general physical appearance of how the occupants live;
- Occupancy profile and demographic including:- gender, age, occupancy rate, employment status, Income, manner in which they pay energy their bills;
- Perceived comfort and standard of living;
- Awareness of energy use usage;
- Typical electrical usage patterns including appliances:- type, number, typical usage patterns;
- Heating system and typical usage patterns;
- Secondary heating. How often used, what is burned and how much.
- Dwelling airtightness;
- Physical or environmental aspects the might affect their energy use.

Post- Upgrading Interview

The nine interviews took place approximately nine months post- completion of upgrading works. The main task was to establish the occupants' perspective of the effect of the upgrading on their standard of living and energy usage. The interviews were purely conversational and open questions which allowed occupants to developed of the feelings and perspectives. Follow on discussions were developed as necessary to help the researcher to gain a deeper insight into their

views. Occupants were also asked how they found the upgrading process itself, and what they found most and least beneficial. In general, these conversations were relaxed and the researcher found the interviewees to be very forthcoming with their views probably due to the rapport that had been developed

3.4.5 Observation

The researcher took mental notes during his encounters and visits to houses as part of the interview process including any casual encounter with the occupants. These observations included trying to establish who actually lived in each house. For example, it became clear that in one particular house that a regular visitor to the house who was introduced as a brother by the occupant appeared to be her partner and was living there on an ongoing long term basis. In this case, the occupant may have been nervous to reveal the true relationship and living arrangement as it may have impacted on either or both of their social welfare allowances. Secondly casual observations were used again as part of the triangulation process. For example the researcher took a mental note if for example there was obvious energy wastage such as a TV, radio or light left on in an unoccupied room.

Other observations included the general living environment and apparent health of the occupants. For example, one of the houses was consistently poorly maintained and unkempt. The researcher noted over a number of encounters the occupants seemed to very often have coughs and colds. In another house, all design ventilation systems were sealed in an attempt to maintain a high internal temperature. The consequence was upon entry to the home the visitor observed a stale odour and high humidity levels.

The researcher had a systematic approach to writing these field notes in a diary following the visits. He sat in the car prior to leaving the area to ensure that good field notes were available for later analysis. Some of these notes were found to be revelatory because, in some cases, the actual behaviour of the occupant did not reflect what was said in the interviews. For example, one of the occupants complained that the house was persistently cold and she would often wear her coat indoors. The researcher noted a number of occasions the occupant would have a single layer of clothing, complaining of the cold, while her husband would have a jumper on.

3.4.6 Coding Methodology

All the interviews and survey-questionnaires were transcribed as soon as practicable after the interviews. Software packages including NVivo or Atlas.ti were considered as qualitative data analytics tools. However, because the sample size was small and a considerable time period would be required to master the software, it was deemed prudent to do the coding manually. A coding system designed in conjunction with the interview and survey-questionnaire. The analysis involved reading and re-reading the interviews to draw out recurrent patterns and instances of note that ran contrary to these patterns. Analytic memos were written in the initial first impression of each interview and these were updated on re-reads. Essentially, certain themes and categories, which had already been developed from the questionnaire, were examined and a number of new categories were added from early stage readings of the transcripts.

Initially, multiple coding was completed and this was then transferred to one version of the data with coloured coordinated and lettered themes. Each interview was examined in relation to a variety of areas and any comments of interest to any of these were colour coded in that persons transcribed interview. The most pertinent information gathered was assigned different categories. All comments from a particular heading were then analysed. Any particularly pertinent comments or observations offered by the respondents were noted separately and these were later used in the analysis section to emphasise or clarify a particular point. When interrogating the data, the main analytical task was to establish what Delamont (1992) terms patterns and regularities in the data. As the concepts of reliability and validity cannot be supported statistically in qualitative research, "*within method triangulation*" (Delamont, 1992 p. 160) was used. This involved systematically correlating the qualitative data with monitored and surveyed data. The aimed outcome was to have a robust, colourful and informative account of the energy use behaviour.

Dwelling airtightness was highlighted as one particularly interesting aspect of energy consumption from the surveys. A system of selective coding was carried out to categorise all related aspects from the interviews. This analysis is dealt with in detail in Chapter 7.

3.4.7 Limitations of the Research

The research approach for this part of the study was qualitative in nature; hence the limitations that go with qualitative research apply, including the possibility of distortion. One of the main limitations is that the findings cannot be easily generalised. In particular, the findings and opinions expressed are specific to the individuals and settings in question. Due to the sample size and the homogeneity of the group results cannot be reported as statistically significant or representative to the population as a whole. However, this homogeneity offered an insight into the particular social class in an Irish urban setting.

3.5 Conclusion

This chapter proposed a novel evidence based methodology for evaluating building energy use. Figure 25 schematically presents the extensive research methodology developed and implemented for the Kilkenny Field study to gather the required data for later analysis. The mixed-methods, multi-Level, multidisciplinary methodology prescribes the use of a three phase triangulation approach to qualitatively and quantitatively verify real energy savings as a result of upgrading and evaluate the reasons why, using survey, monitored and interviews data.

The first stage is the quantitative data collection. This took the form of the BER's, airtightness testing, and design, installation and measuring of energy use using a bespoke monitoring system. The second consisted of mixed mode qualitative data collection using a combination of ethnography, phenomenology and semi-structured interviews.

Drawing on the lack of real life data for whole house energy use patterns, a baseline of energy usage must first be established from which improvements and efficiencies can be measured.

The concepts and techniques presented aim to enhance the reliability of the findings and have the following advantages:

- Credibility when verifying energy saving as a result of upgrading;
- Scalability of the monitoring system;
- A systematic approach to gathering data for future assessment and analysis;
- Brings the very important aspect of the occupant into the study which has been highlighted as lacking in most previous energy monitoring studies.

The extensive triangulation within the project aims to add both breadth and depth. In such a relatively new research area, the knowledge gained adds to the general body of knowledge previously available.

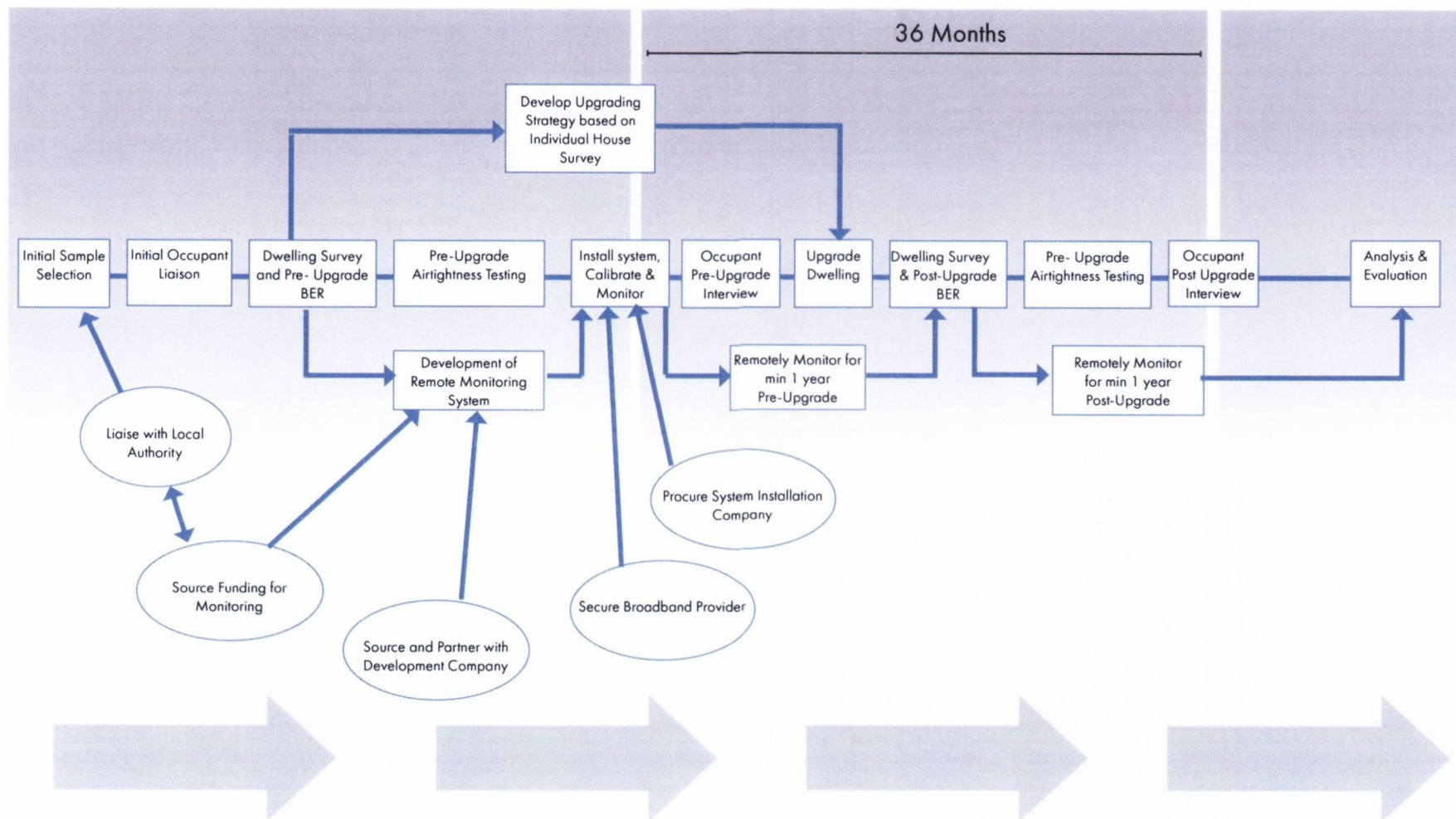


Figure 25 Flow chart of three phase methodology to establish and evaluate dwelling energy use

Chapter 4

4 Field Study – Preliminary Study Examining Social Housing Energy Performance and Airtightness in Waterford

4.1 Introduction

Waterford City is situated in the South East of Ireland (see Figure 26) and has a permanent population of 46,732 (CSO, 2011). The Waterford City Council (WCC)² housing department has a good relationship with Waterford Institute of Technology. The City Council were keen to have an independent study completed on a sample of the existing social housing stock in 2009 and asked the researcher to carry out this study. WCC managed in excess of 3000 social housing units at the time of the study. These houses range in age from the mid- 1800s to those completed in 2008. While a database of the exact house types is currently not available, they vary between two and three bedroom, detached, semi-detached and terraced, of solid wall and cavity wall construction. The majority of social houses in the Waterford City area are typical two-storey, three bedroom, semi-detached and of cavity wall construction, as shown in Figure 27. In Ireland, 70% of the existing housing stock, was built prior to 1991, 88% of which was built prior to 1980 when minimum insulation standards were implemented (CSO, 2011).



Figure 26 Map of Ireland showing location of Waterford and Kilkenny City (Source: Google Maps)

² On May 31st 2014, Waterford City Council and Waterford County Council became one legal entity called "Waterford City and County Council"

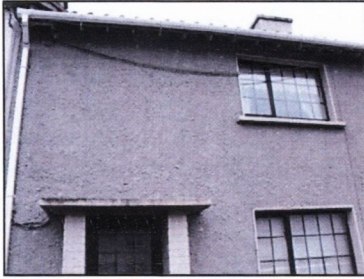
WCC is charged with task of maintaining a large number of ageing houses where insulation and heating system standards are much lower than current minimum building regulation standards. These houses offer good potential for energy savings from energy efficient upgrading. The project brief was developed in conjunction with the WCC representatives. The LA expressed an interest to establish the current BER's and airtightness characteristics of a sample of their stock across a range of ages. This was to allow them to develop an upgrading strategy for their older dwellings and examine the energy performance and build quality of their newer stock. The researcher felt it was critical to conduct a study in a social housing area prior to the main study in Kilkenny for the following reasons:

- Firstly, the occupants are not the dwelling owners. This meant that the researcher would also have to deal with a third party, namely the council. This would mean developing relationships and mechanisms to gain access to tenants homes, who would be willing to partake in the study;
- Secondly, the study offered the researcher an opportunity to establish the most appropriate mechanisms to appraise, liaise and communicate with social housing tenants. There was going to be expensive equipment involved and used in the study. Some of the areas being studied had a long history of anti-social behaviour. Therefore, apart from there being issues with the equipment many of the residents would likely be resistant to dealing/cooperating with any form of officialdom. Even if some of the occupants agreed to take part in the study it was likely that the council would suggest that they not be included. This is because even the council officials would not go into certain dwellings because of serious drug and crime issues that a small number of the residents are involved in.
- This study offered the researcher time to develop the skills and knowledge required to carry out the technical aspects of the BER's and airtightness testing.

Volunteers were sought and there was no pressure placed on tenants to partake in the study. The initial meetings with the LA were followed by weekly consultation meetings as well as multiple phone calls over a three month period between the LA Representatives, LA Community Liaison Officers and 40 householders. No form of incentive was on offer to the householders. Twenty eight households who were deemed trustworthy by the LA agreed to the study following a consultation period. This was the researcher's first experience dealing with tenants and this learning curve proved useful when dealing with tenants in the main study in Kilkenny.

Three locations with dwellings of different age categories were selected:

- pre- 1975 (Figure 27a);
- circa 1980 (Figure 27b); and
- completed in 2008 (Figure 27c).



a) Pre- 1975 house type



b) 1980's house type



c) 2008 house type

Figure 27 Typical house type for each age category

A systematic approach was adopted to complete the house surveys, BER's and Airtightness testing on twenty eight occupied single family residential semi-detached and terrace houses ranging in age from 1944 to 2008 in three discrete housing estates. The results are compared to past studies and compliance with the existing standards at the time of testing in 2009. The relationship of construction type, age range, design details, and effect of retrofitting on air permeability is examined. An evaluation is made of the effect of including blower door results in the BER calculations is also presented.

4.1.1 Building Typology

The buildings studied were of similar construction type; dwellings have two-storeys, three bedrooms, slab-on-grade floors, load bearing external cavity walls and cold roof construction. The average floor area and volume of the studied houses was 80m² and 202m³, respectively. Natural ventilation is provided by passive wall vents designed with closable hit and miss or permanently open louvered vent grilles in each room. However, many of the pre- 1975 houses have no wall vents. A number of the pre-1975 and 1980's dwellings had undergoing different phases of an energy efficiency retrofit scheme. The full retrofitting process of each of the houses consisted of four operations:

- Installation of new double glazed windows and doors (DG);
- Placing bonded- beaded cavity wall insulation (CI);
- Placing 200mm glass fibre insulation in the attic (AI);
- Installation or upgrading of gas fired central heating (CH).

Hereafter, complete retrofitting refers to all four operations being complete and partially complete refers to any three or less of the operations being complete.

Chan *et al.*, (2005) found that US dwelling air-tightness can be normalised according to year of construction and divided the database into four broad age categories. This study adopted a similar approach, grouping the dwellings in three categories, based on year of construction, as shown in Table 3.

Category	Number of Houses	Comments
Pre- 1975 (see Figure 27a)	8	Typical of the older housing stock in the Ireland. Year of construction ranges from 1944 to 1974. Broadly similar construction: 100mm cavity with no insulation provided at construction.
1980's (see Figure 27b)	13	Typical of houses constructed prior to the implementation of minimum insulation standards in Ireland. 100mm cavity with no insulation provided at construction. Typically nominal 100mm fibre attic insulation provided at construction stage which has degraded over time, providing little insulation value. In some cases no attic insulation was present.
2008 (see Figure 27c)	7	All houses tested were part of one development of over 70 houses. Brick outer leaf and block inner leaf wall of 100mm cavity wall construction with full fill bonded bead insulation, 200mm of attic insulation, gas fired central heating and double glazing. Mechanical extractor fans fitted in bathrooms. The houses typically have a draught lobby to the front and WC to the rear of the building. Built in compliance with the building regulations.

Table 3 Dwellings studied grouped by year of construction

4.2 Measurement Results

The mean air permeability of the test result dataset presented in Table 4 was 9.1 m³/hr/m², with the minimum 5.12 m³/hr/m² recorded in a pre-1975 terrace house, and maximum 14.42 m³/hr/m² recorded in a 1980's semi-detached house. Figure 28 demonstrates that 50% of all dwellings exceeded the Technical Guidance Part L 'reasonable upper limit' which at the time was 10m³/hr/m² (DEHLG, 2008).

When the dwellings were sub -divided by age category, counter intuitively, the older buildings overall were more airtight than the new dwellings with the pre-1975 dwellings, 1980's dwellings and 2008 dwellings mean air permeability of $7.5\text{m}^3/\text{hr}/\text{m}^2$, $9.4\text{m}^3/\text{hr}/\text{m}^2$ and $10.4\text{m}^3/\text{hr}/\text{m}^2$ respectively. The air permeability of the 2008 dwellings ranges from $6.02 - 13.24\text{m}^3/\text{hr}/\text{m}^2$, with just 2 from 7 houses tested within $10\text{m}^3/\text{hr}/\text{m}^2$ upper limit. These results show that contrary to common belief newer buildings are not necessarily more airtight buildings. Potential reasons for this are discussed in Section 4.2.4.

House Number	Year of	Construction Type	Retrofit Complete*	Envelope Area m ² (A _E)	Internal Volume m ³ (V)	Ave Air Changes @ 50Pa (ACH)	Ave. Air perm @ 50Pa (m ³ /hr/m ²)	Air Flow Exponent n	Change in kWh/m ² /yr including test results (%)
Pre- 1975									
1	1941	Terrace	DG, CH	219	171	10.96	10.45	0.630	+ 1
2	1958	Semi-Detached	DG, CH, AI, CI	187	8.38	8.38	7.85	0.610	- 2
3	1961	Terrace	None	189	175	5.53	5.12	0.622	- 7
4	1963	Terrace	DG, CH, AI, CI	180	163	5.46	5.20	0.670	- 4
5	1963	Terrace	DG, CH, AI, CI	180	163	6.30	6.02	0.641	- 5
6	1966	Terrace	DG, CH, AI, CI	192	180	8.26	7.75	0.609	- 6
7	1973	Semi-Detached	CH,AI,CI	204	195	9.28	8.45	0.654	- 5
8	1974	Semi-Detached	CH	220	211	9.98	9.08	0.654	+ 1
1980's									
9	1980	Semi-Detached	DG, CH, AI, CI	215	205	6.31	5.96	0.623	- 5
10	1981	Semi-Detached	none	215	205	11.66	10.64	0.658	+ 4
11	1981	Semi-Detached	CH,AI	215	205	10.89	10.38	0.670	- 2
12	1981	Semi-Detached	CH,AI	215	205	10.89	10.39	0.650	- 2
13	1981	Semi-Detached	CH,AI	215	205	11.12	10.60	0.625	- 2
14	1981	Semi-Detached	DG, CH, AI, CI	215	205	9.44	9.00	0.622	- 1
15	1981	Semi-Detached	CH,AI	215	205	11.74	11.19	0.634	+ 1
16	1981	Semi-Detached	none	215	205	14.90	14.42	0.644	+ 3
17	1981	Semi-Detached	CH,AI	215	205	14.54	13.86	0.626	+ 1
18	1981	Semi-Detached	DG, CH, AI, CI	215	205	11.07	10.55	0.645	- 1
19	1986	Semi-Detached	DG, CH, AI, CI	215	205	5.61	5.35	0.671	- 5
20	1986	Semi-Detached	DG, CH, AI, CI	215	205	5.39	5.14	0.649	- 5
21	1986	Semi-Detached	DG, CH, AI, CI	199	188	5.55	5.25	0.668	- 3
2008									
22	2008	Semi-Detached	none	246	224	11.44	10.90	0.617	+ 1
23	2008	Semi-Detached	none	250	221	13.99	13.34	0.642	+ 1
24	2008	Semi-Detached	none	246	224	9.02	8.60	0.653	- 2
25	2008	Semi-Detached	none	246	224	12.19	11.69	0.651	+ 1
26	2008	Semi-Detached	none	246	224	11.84	11.36	0.635	+ 1
27	2008	Semi-Detached	none	246	224	11.58	10.72	0.637	+ 1
28	2008	Semi-Detached	none	246	224	6.65	6.02	0.624	- 4

*DG - Double Glazing, CI - Cavity Wall Insulation, AI - 200mm glass fibre attic insulation, CH - Gas fired central heating system where there was none.

Table 4 Table Measured air permeability and related parameters of dwellings in this study

Smoke pencil test observations correlated with previous research (Sherman and Chan, 2003, Jaggs and Scivyer, 2006a) uncovering an array of different leakage paths. Typical leakage locations were junctions between floor and wall at 1st floor level, gaps around attic hatch, letterbox, leakage through and around windows and doors, penetrations in envelope for plumbing and electrical installations such as light switches and sockets, fire alarms and around waste pipes.

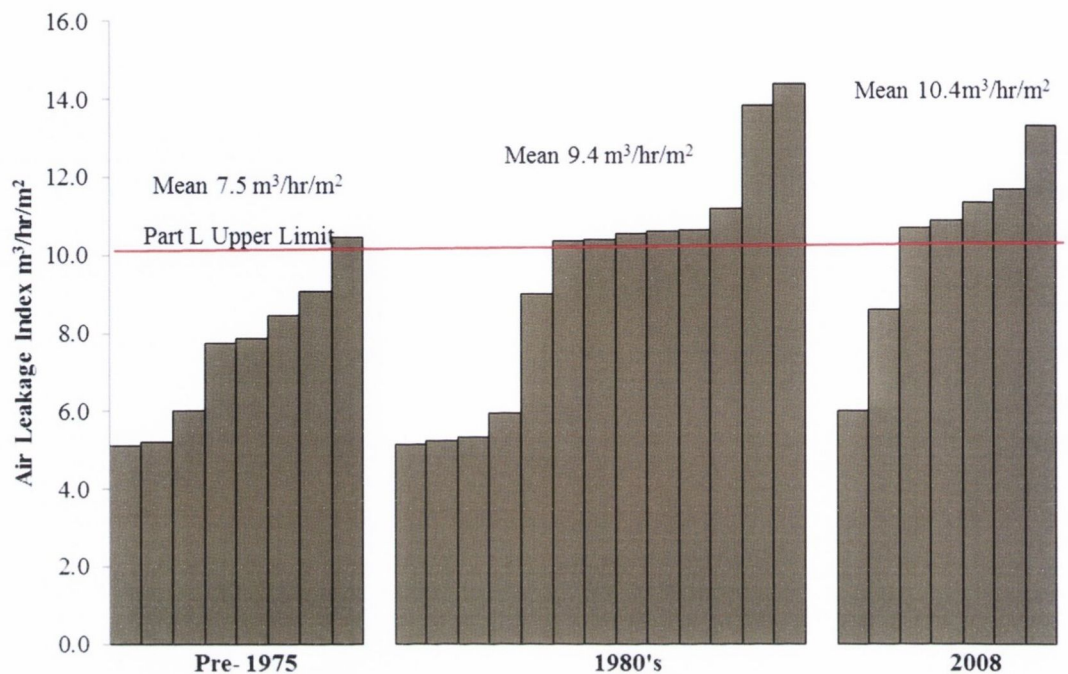
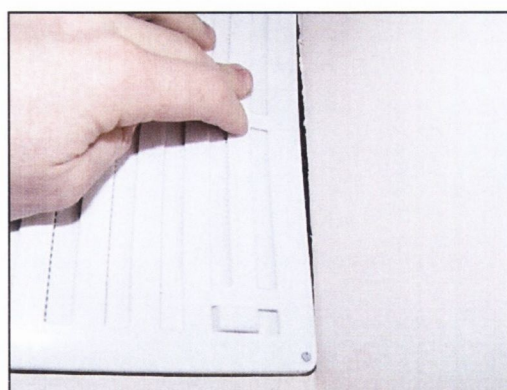


Figure 28 Measured air permeability of dwellings studied, categorised by age (n =28)

It is worth noting that intentional passive vents in many houses were not sealed to the external wall and large gaps remained when the slotted vents when closed, as shown in Figure 29 a and b. Significant leakage occurred through accidental voids in the stud partition internal walls at first floor level of 1980's houses, as shown in Figure 29c. Piecemeal sealing was frequently of poor quality using unsuitable materials and often ineffective, as shown in Figure 29d.



(a)



(b)



(c)



(d)

Figure 29 Typical leakage paths: a and b) passive wall vents, c) accidental hole in plasterboard and d) plumbing to attic.

4.2.1 Energy Performance

Table 4 presents the change in theoretical energy consumption ($\text{kWh}/\text{m}^2/\text{yr}$) from BER's, contrasting the DEAP algorithm method (Method A) and the inclusion of actual airtightness tests results (Method B). The change in theoretical energy consumption was calculated by $(\text{Method B} - \text{Method A})/\text{Method A}$, expressed as a percentage. In general, the DEAP algorithm yielded slightly conservative results and overestimated the air permeability of the dwellings think you have to suggest a possible reason. Nominal 5% reduction in theoretical energy was recorded for the retrofitted dwellings when airtightness test results are included. For example, in dwelling No. 3, an as-built terrace house, the calculated reduction is 7%. Some notable exceptions are the 2008 houses where theoretical energy increased in 5 from 7 dwellings by 1%. This demonstrates that BER predicted energy use tallies when airtightness results are included, but that the influence of building fabric, such as in the case of retrofitting, should be considered in more detail.

4.2.2 Dwelling Age and Stage of Retrofit

The pre-1975 dwellings yielded the lowest mean permeability of 7.5 m³/hr/m². This was considerably lower than the 1980's and 2008 dwelling results having a mean of 9.4 m³/hr/m² and 10.4 m³/hr/m² respectively. Figure 30 and Figure 31 illustrate that retrofitting had a positive effect on air-tightness. Partial retrofitting of the 1980's dwellings, having an identical construction type, showed little improvement in leakage rates compared to as built dwellings. This suggests that placing attic insulation and installing central heating systems (often cited as adding to building leakiness) has a nominal effect on airtightness. However, the study shows that cavity wall insulation and installing double glazing offer the greatest impact, reducing air permeability by 28% and 39% for the pre-1975 and 1980's dwellings respectively.

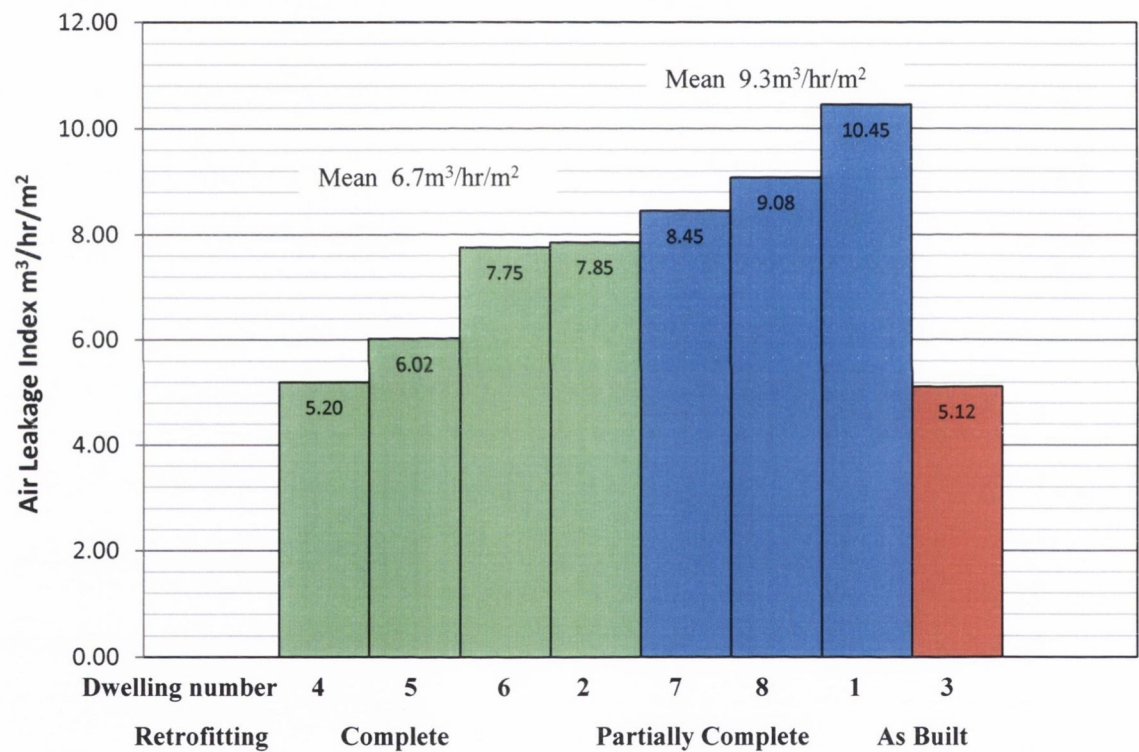


Figure 30 Air-tightness measurements of pre-1975 dwellings categorised by stage of retrofit

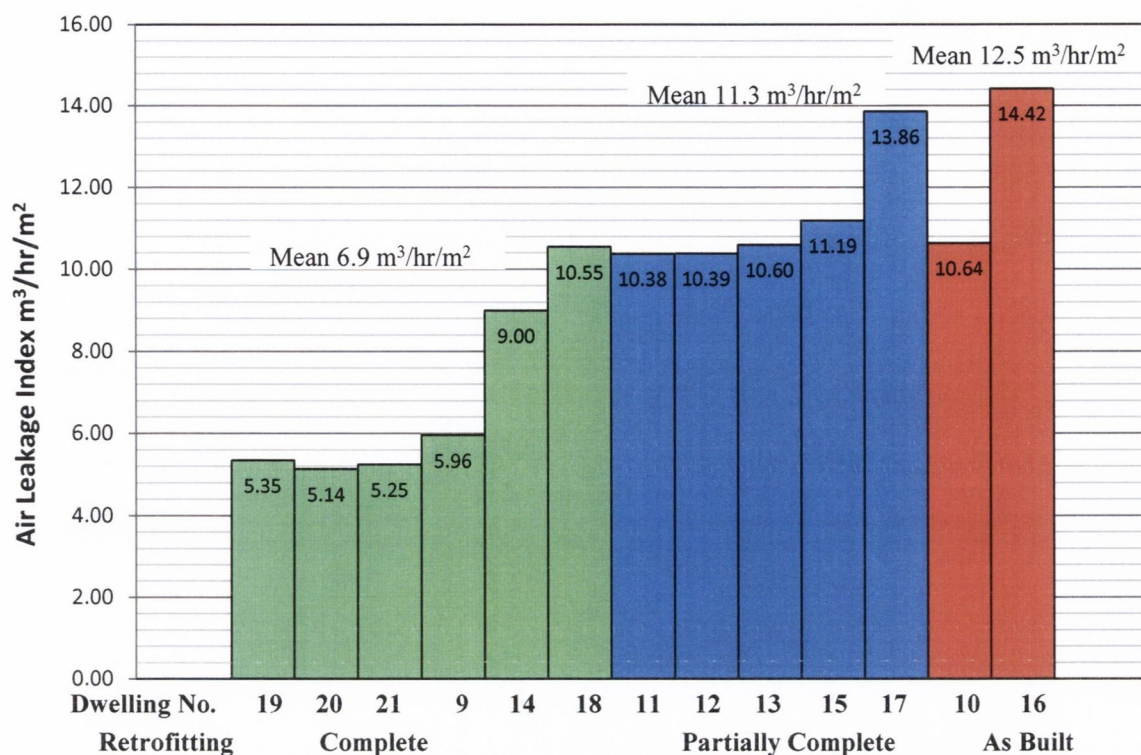


Figure 31 Air-tightness measurements of 1980's dwellings categorised by stage of retrofit

With no modification since construction, dwelling No. 3, as shown in Figure 30, was an anomaly, having the lowest air permeability of $5.12 \text{ m}^3/\text{hr}/\text{m}^2$. The survey found that the single glazed windows were in good condition and, in many cases, had been painted such that the windows could not be opened. The house did not have any permanent wall vents or central heating system, which meant there were minimum openings through the buildings envelope.

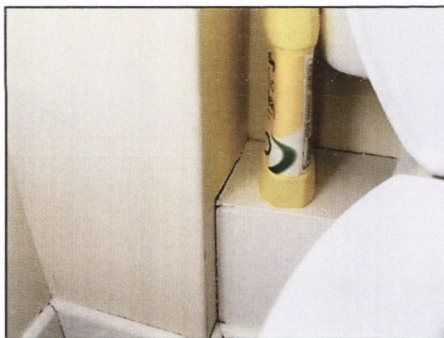
4.2.3 Exponent, n

The average flow exponent, n , at 50 Pascals, for each dwelling, is presented in Table 4. The airflow exponent can be used as an aid to describe the flow regime through the envelope. Ranging between 0.5 and 1, n values approaching 0.5 indicate turbulent airflow through rather large apertures, while values closer to 1 indicate laminar flow through small cracks and holes (ATTMA, 2010). From the dataset average of 0.64, it is evident that flow regimes are towards the turbulent end of the spectrum, indicating air leakage through the large apertures. These results provide positive correlation with the findings of the surveys and smoke pencil test.

4.2.4 Design and Workmanship

There is often the perception that newer dwellings are more airtight than older buildings. However, Figure 28 demonstrates that 5 from 7, 2008 dwellings tested exceeded the Part L reasonable upper limit of $10\text{m}^3/\text{hr}/\text{m}^2$. The dwellings were part of one development; all had full fill cavity insulation, double glazing and 200mm attic insulation. Surveys and smoke pencil tests, in addition to common leakage paths, identified the critical leakage pathways as follows:

- c) The internal soil vent and waste pipes were located inside the building envelope with the pipes extending from the ground floor, through the attic and exiting through the roof. Although the pipes were concealed within a service duct, the joints to internal walls were not sealed as shown in Figure 32a. Thence, this provided a leakage pathway into the attic space.
- d) The window frames were not fitted correctly. The draught seal was partly detached from the frame, or even completely missing, as shown in Figure 32 b and c. This also created leakage pathways.
- e) Many of the wall vent covers were not sealed correctly to the walls, thus leakage pathways remain when vent were closed, as shown in Figure 32d.



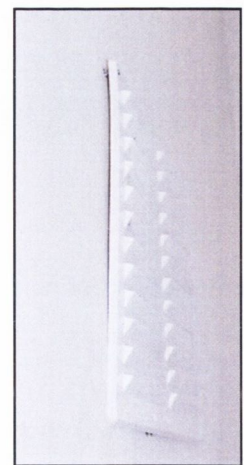
(a)



(b)



(c)



(d)

Figure 32 Critical leakage pathways for 2008 dwellings

The results do not correlate with research by Pan (2010) and Chan (2005) who found evidence suggesting that airtightness of newer dwellings has increased compared with older dwellings. However, the survey does support Kalamees (2007) finding that workmanship and supervision had a large effect on building airtightness. The results clearly demonstrate that good design, detailing, specification of materials and construction practice is of fundamental importance when constructing new houses.

4.3 Conclusions

The field study provides data set of air permeability measurements for a range of new and retrofitted single family dwellings. Air permeability testing was carried out using a Retrotec Q46 Automated Blower-Door in accordance with the ATTMA Technical Standard. The 28 houses included in the survey comprised three periods of house building in Ireland ranging from 1941 to 1974 and 1980 to 1986 and more recent construction in 2008. In each case, the construction method involved cavity wall construction; which meant that the survey allowed a critical assessment to be made of the airtightness properties of modern compared with retrofitted cavity wall houses. The outcome of the survey summarised below highlights the importance of workmanship and construction detailing in order to achieve the airtightness standards set in current Irish Building Regulations. The field measurements indicate that in the case of retrofitted properties there is a direct link between improved insulation of cavity walls, double glazing and airtightness. Whereas for the modern 2008 construct properties the increased provision of wall and roof insulation still lead to relatively high air leakages in excess of $10\text{m}^3/\text{hr}/\text{m}^2$.

The key findings are summarised as follows:

- 1) Testing found the mean air permeability of the pre-1975, 1980's, and 2008 dwellings to be $7.5\text{ m}^3/\text{hr}/\text{m}^2$, $9.4\text{ m}^3/\text{hr}/\text{m}^2$ and $10.4\text{m}^3/\text{hr}/\text{m}^2$ respectively. The air permeability of 5 from 7, 2008 dwellings tested were in excess of the $10\text{m}^3/\text{hr}/\text{m}^2$, while the most air-tight dwelling, at $5.12\text{m}^3/\text{hr}/\text{m}^2$, was constructed in 1961. As a result, new dwellings cannot automatically be assumed more air-tight than older dwellings.
- 2) Leakage paths in the dwelling were wide-ranging and non-uniform across all dwelling ages. Smoke pencil testing found a number of pathways but there were many hidden and inaccessible. Air flow exponent records identified airflow as being through rather large apertures.

3) For relatively air-tight dwellings, the inclusion of air-tightness test results can have a positive influence on dwellings Building Energy Rating (BER). Calculated energy use for the most air-tight dwelling reduced but 7%. Inversely for the less air-tight 2008 dwelling energy use increased by 1%.

4) Retrofitting dwellings can have a considerable positive effect on air-permeability. While attic insulation and installing central heating systems had a nominal effect on air-tightness, combined with full fill cavity wall insulation and double glazing, the air permeability of the dwellings tested was on average 35% lower than houses which had not undergone upgrading.

5) In the 2008 dwellings, poorly designed and executed on site the internal soil vent and waste pipes provide a significant leakage path to the attic. Also, poorly manufactured and installed windows and passive wall vents allows considerable leakage pathways through the building envelope.

This study highlights the lack of practical research in airtightness for new and retrofitted dwellings in Ireland. The results may form a basis to policy makers and designers towards making informed decisions about improving air-tightness of new and existing dwellings. The study is limited when drawing conclusions as the dataset is limited and does not represent the characteristics of every dwelling type in Ireland. Furthermore, while the dwellings described in this paper were of similar construction, to ensure a robust dataset when comparing the effect of upgrading on airtightness, tests should be carried out on each dwelling pre- and post- upgrading.

Chapter 5

5 Field Study - Kilkenny

5.1 Introduction

This chapter describes the application phase of the methodology described in Chapter 3 on social housing in Kilkenny. Kilkenny City, the county town of Co. Kilkenny, has a population of 24,423 (CSO, 2011). Kilkenny County Council (KCC) is responsible for the management of 2138 housing units in both urban and rural settings. Funded through the 'Social Housing Investment Programme' (SHIP) the LA planned to upgrade approximately 90 properties in 2012. KCC wished to evaluate, in depth, the actual benefits of their upgrading practices to become exemplars to other local authorities involved in upgrading works. As a result, KCC agreed to support the longitudinal study for two years through a fiscal investment in the monitoring equipment for a defined number of houses.

5.1.1 Dwelling Selection

Wingfield *et al.*, (2008) says that it can be difficult to get people to agree to having their energy monitored. The researcher had gained valuable insights in developing good client researcher relations from the Waterford study. Lessons learned from Waterford were used to develop the dwelling selection and survey processes. An intensive desk study was completed to identify potentially willing households in consultation with KCC Department of Housing officials and KCC Tenant Relations Officers.

There were several issues that need to be taken into account. Consideration had to be given to the security of the expensive monitoring equipment. Council officials felt that a number of homeowners could be careless. Therefore, care was taken in the selection process to mitigate against the potential for the equipment to be damaged or removed. Nine households willing to partake in the study from those scheduled to be upgraded were deemed to be suitable. These were selected from over twenty that were identified and visited. These units are representative of the majority of KCC housing stock and similar to other local authorities' provision nationally. However, though logical dwelling selection criteria was used, such as occupant willingness, care needs to be given if extrapolating the results to the whole Social Housing Sector. This was a limitation of the study in that the dwellings selected were not representative of all social housing in Kilkenny. This was outside the control of the researcher as the council were only willing to invest money into upgrading where they deemed they would get the co-operation of the tenants.

The nine houses selected were grouped in two discrete locations approximately 3km apart within the City Environs, as shown in Figure 33, Figure 34 and Figure 35. The houses were scheduled for upgrading in summer 2012. Given that the sample is statistically small, the selection process aimed to keep the dwelling construction type as homogeneous as possible. This uniformity reduces the number of physical variables to allow occupant behaviour to be assessed which Brown *et al.*, (2011) concludes has a large effect on energy consumption.

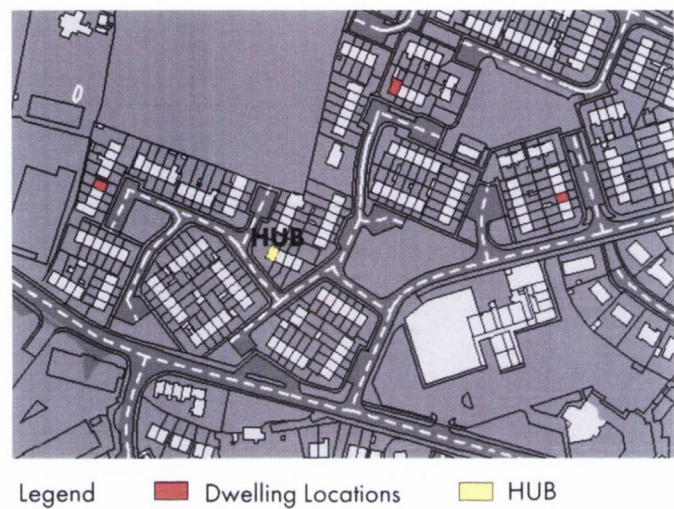


Figure 33 Location 1 - Dwellings A, B, C & D



Figure 34 Location 2 - Dwellings E, F, G, H, and Hub

The hub for location 1 was situated in the attic of dwelling C. Broadband was sponsored by permaNET.ie. The hub for location 2 was situated in the local community centre which had a broadband connection.

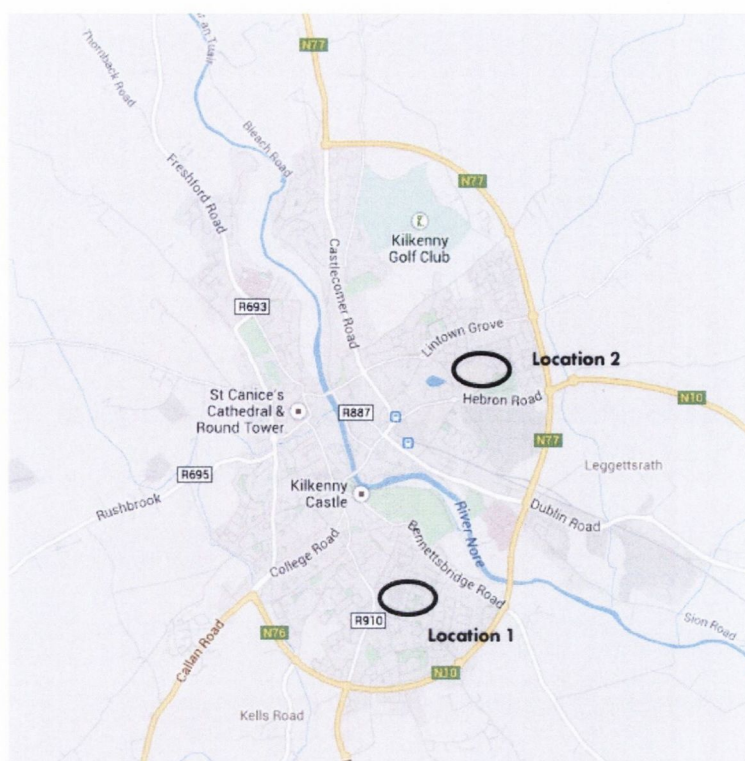


Figure 35 Site Locations within Kilkenny City Environs

5.1.2 Dwelling Typology and Occupant Profile

The nine dwellings, built circa 1980, are occupied single family social residential semi-detached and terraced houses. Full details, gathered in phase 1 and 3, are provided in Table 5. Combined terrace and semi-detached houses account for the largest proportion, 44.8%, of dwellings in Ireland (CSO, 2007). The average floor area of the three-bedroom two-storey (see Figure 36) and two bedroom single storey houses (see Figure 37) is 80m² and 50m² respectively, with the exception of house D which has a single storey extension to the rear, giving an increased floor area of 87m². All dwellings have load bearing external cavity walls and are naturally ventilated. Ground floors are slab-on-grade with suspended timber first floors. Ground floor internal walls are of solid block construction, while stud partitions are in place at first floor level. The attic space is of typical cold roof construction with insulation between ceiling joists. Preceding refurbishment schemes upgraded all windows to double glazing and back boiler heating systems replaced with natural gas central heating. House D retained their solid fuel cooker with back boiler.

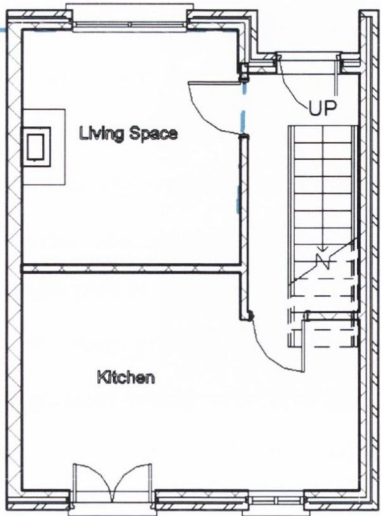
Dwelling	Classification	Floor Area m ²	Orientation	Number of Occupants	Occupants Age					Weekly Income €
					5 – 17	18 – 25	26 – 45	46 – 55	56 – 65	
A	2 ¹ , T ²	80.6	E - W	1				F		210
B	2, S	89.0	E - W	2					F ³ M ⁴	500
C	2, S	76.9	E - W	3	M	M	F			390
D	2, T	87.7	E - W ⁵	3		M		F M		440
E	2, T	75.0	N - S	3	M F		F			268
F	2, S	76.0	N - S	1				F		220
G	2, T	79.8	N - S	3	M F		F			430
H	1, S	46.2	N - S	1					F	210
J	1, S	49.8	N - S	2					M F	352

¹ 1 or 2 storeys high
² T = Terrace, S = Semi-detached
³ Female
⁴ Male
⁵ E - W East - West
N - S North - South

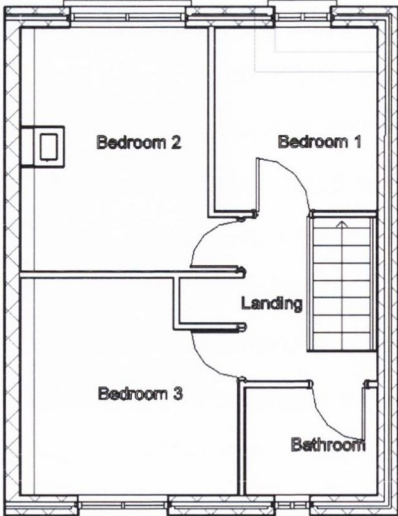
Table 5 Dwelling details, occupant profile and weekly household income



Dwelling C



Ground floor Plan

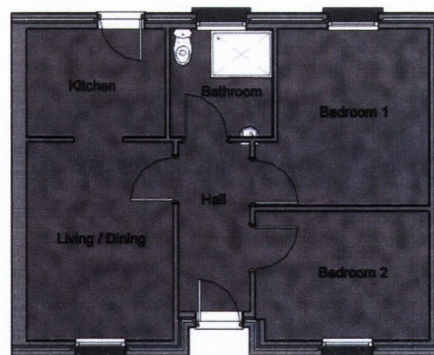


First Floor Plan

Figure 36 Typical Two Storey Dwelling



Dwelling H



Floor Plan

Figure 37 Typical Single Storey Dwelling

5.2 Upgrading Strategy

The Department of the Environment, Community and Local Government allocates capital funding to LA's through the Social Housing Investment Programme (SHIP) to improve the standard and quality of their stock. The level of funding allocated to increase energy efficiency is based on verified energy savings made by improving the buildings fabric and installing high-efficiency condensing boilers. Savings are verified comparing pre- and post- upgrading BER energy performance results. Funding is awarded on a sliding scale of verified savings. LA's are eligible to claim a maximum 90% of the cost or €18,000, whichever is the lesser. The minimum contribution from the LA is 10% of the cost of the upgrading. Department of Environment Heritage and Local Government Circular SHIP 2011/05 'Improving the Social Housing Stock' Appendix A, as shown in Appendix A, sets of funding limits based on proportional savings and eligible works.

The upgrading strategy was developed to comply with the eligible works under SHIP and focused on improving building fabric, primary and secondary heating systems and controls. The DEAP software tool was used to determine the relative energy efficiency benefits of various design improvements. A matrix of potential upgrading interventions led to the development an optimal upgrading strategy for each of the dwellings. The final agreed strategy with KCC for upgrading went beyond the scope of SHIP and minimum requirements set out by DEAP. This included winterising the attic cold water storage tank and pipework, installing design ventilation to comply with Part F of the building regulations and installing fire and carbon monoxide monitoring systems. The general uniformity of the dwellings meant a simplified standardised strategy could be developed, with some minor additions. This was beneficial for the LA, making the procurement process straightforward and tendering competitive. The common upgrading strategy for each dwelling is outlined in Section 5.2.1, and location specific upgrading outlined in Section 5.2.2. The strategy may be classified as a shallow upgrading strategy.

5.2.1 Upgrading Common to all Dwellings

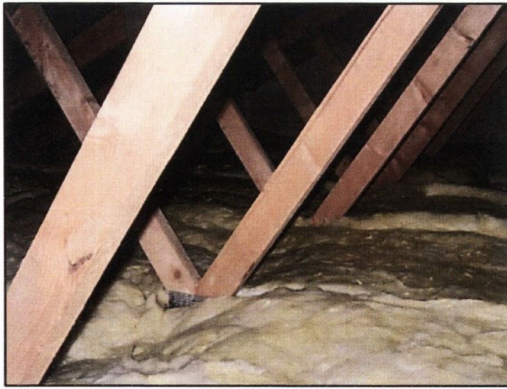
The common upgrading approach for all the dwellings included:

Cavity Wall and Attic Insulation

All works were carried out in accordance with the system supplier's specification and relevant systems NSAI Agrément Certificate.

- All exposed cavity walls were insulated with pumped beaded insulation of maximum thermal conductivity of 0.033 W/mK;
- In addition to the existing insulation the attic space was insulated with a minimum depth of 300mm with fibre rolled insulation with a maximum thermal conductivity of 0.044 W/mK, see Figure 38a;
- All pipework new and existing exposed was lagged with 20mm wall thickness Armaflex pipe insulation, and joints sealed with Armaflex lagging tape. No exposed pipework or fittings allowed;
- New cold water storage tank (CWS) housing and insulation was installed with 12mm WBP insulated internally to meet the standards as outlined in Part L of the building regulations Figure 38b;
- Draught stripping was applied to the attic door and two holding latches installed and 100mm HD insulation to top side of attic door, Figure 38d.

All pipe and water storage tank insulation and installation was in accordance with BS 5970 Code of Practice for thermal insulation of pipework and equipment in the temperature range of -100°C to +870°C and BS 5422 Method for specifying thermal insulating materials for pipes, tanks, vessels, ductwork and equipment operating within the temperature range -40°C to +700°C. The area under the cold water storage tank was not insulated for cold weather purposes.



a) Upgraded Attic Insulation



b) CWS prior to upgrading



c) Attic hatch prior to upgrading



d) Attic hatch with holding down latches

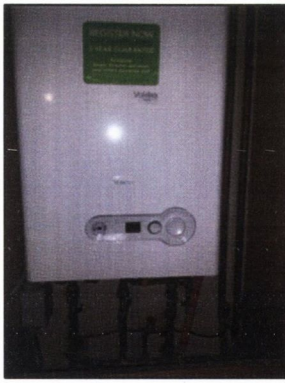
Figure 38 Generic upgrading for all dwellings

Heating, Hot Water & Controls

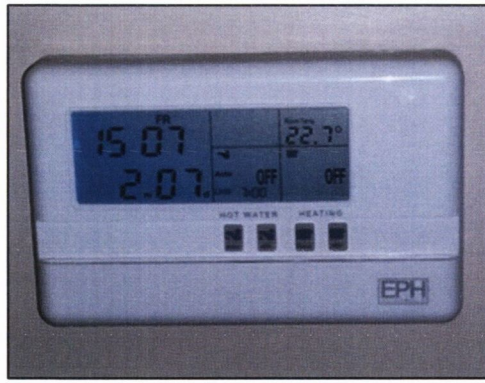
Existing gas boilers were replaced with gas condensing wall mounted boiler with a certified minimum seasonal efficiency of 90% and installed to RGI and manufacturers guidelines, as shown in Figure 39a. A 3 zone control system with a 24 hr 7 day digital programmer as shown in Figure 39b replaced the existing single zone and time clock arrangements. The standard domestic 3 zones arrangement is:

- ground floor space heating;
- first floor space heating; and
- separate hot water.

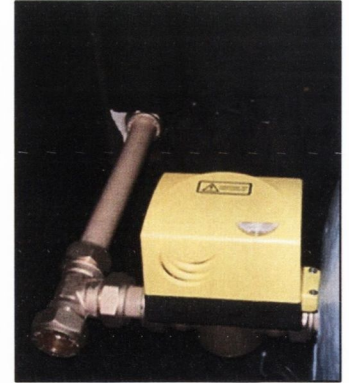
Each zone is operated by motorised valves, as shown in Figure 39c. A boiler interlock was installed to allow independent control of SWH in terms of time and temperature. Wall thermostats in the upstairs landing and downstairs hall control the zoned space heating.



a)



b)



c)

Figure 39 Upgraded Condensing Boiler (a) programmable heating controls (b) and motorised valves

Existing hot water cylinders were replaced with new 98L, 30mm factory insulated cylinders to 2008 building regulations (0.8W/L), as shown in Figure 40. Electric immersions were upgraded to have time and temperature control.

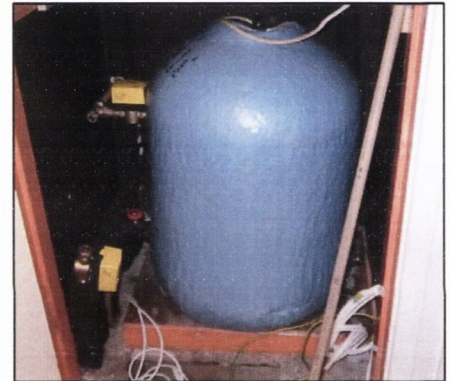
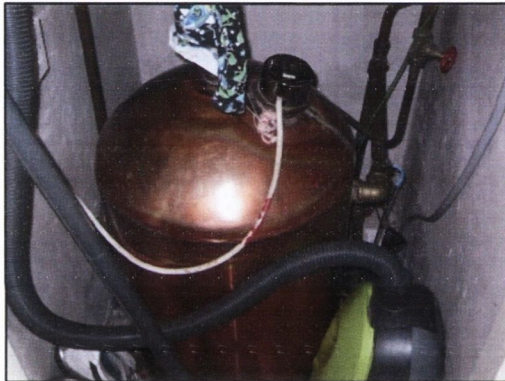


Figure 40 Existing copper cylinder replaced with new factory insulated cylinder and motorised valves to control system zoning

Solid Fuel Stoves

Existing open fireplaces and surrounds were removed and replaced with Stanley Cara 5kW Insert Multi Fuel Stove, as shown in Figure 41. These stoves have an efficiency rating of >80% when installed to manufacturer's guidelines.



Figure 41 Stanley Cara Insert Stove and surround fit at Dwelling D

Windows & Doors

All dwellings had uPVC window upgrades as part of previous upgrading initiatives. Many hinges and seals were in a poor state of repair as shown in Figure 42. Where existing windows and doors were retained, all damaged seals and hinges replaced and new 'J- Rails' fitted to bottom of front and back doors as required.



Figure 42 Poor window seal blocked with kitchen paper in Dwelling F

Ventilation

All dwellings were constructed circa 1980 when building regulations were not well established or enforced as in the present time. Many were found to be under ventilated during the dwelling surveys. All upgrades made provision to ensure that each dwelling was made compliant with Building Regulations 2009, Technical Guidance Document F – Ventilation. The requirements varied by dwelling and included fitting:

- mechanical hood extract fans and constant open passive vents in the kitchen;
- constant open louvered passive vents in the sitting;
- hit and miss vents in all bedrooms;
- mechanical wall vents with an automatic overrun wired into light switch was installed in the bathroom.

Where there were vents, they were cleared of any debris or blockages. The external walls were core drilled, sleeved with a 125mm internal PVC pipe and appropriate vent cover attached where new penetrations were required.

Lighting

Low Energy 'A' rated CFL bulbs in accordance with EC 244/2009 were fitted throughout the dwellings.

Ancillaries

New mains operated smoke alarms, with a battery back-up, were fitted to hall and landing.

5.2.2 Custom upgrading of select dwellings

A number of dwellings required additional or unique upgrading interventions. These included:

Dwelling D

Extension

The existing flat roof was removed and replaced with timber batons, ¾" WPB Plywood, 50mm HD Insulation and finished with Firestone Rubber Cover EPDM membrane covering. All external walls and ceiling were dry lined with a minimum 52.5mm of Kingspan K18 board, returning 32.5mm into window reveals. Reveals were cut back (top, bottom and both sides) to ensure 35mm of window frame exists after skimming.

Windows & Doors

New PVC doubled glazed windows were installed to the entire house. All windows have integrated trickle vents a maximum U-Value of 1.5 W/m²K, Frame Factor of 0.71, and Solar Factor of 0.70g. The front door was replaced with a hardwood door with U-value not greater than 2.7 W/m²K. French doors were installed to replace the existing rear sliding patio door. Windows and doors were draught proofed with Siga draught proof tape around all openings.

Heating & Hot Water

Central heating was provided by a solid fuel cooker located in the kitchen prior to upgrading. The existing solid fuel cooker was replaced with gas condensing wall mounted boiler in the extension. This was installed to RGI and manufacturers guidelines with an expected minimum seasonal efficiency of 90%.

Dwelling J

The existing open fireplace was permanently sealed by the occupants. A new gas fire was fitted in lieu of a standard multi-fuel stove being installed.

Dwellings E, F, G, H and J

Front and rear doors were replaced with new uPVC doors with U-value of 3 W/m²K.

The contractors had to take into consideration that the occupants were to remain resident throughout the works. Thus, it was imperative to minimise disturbance of the occupants. The programme for completion of works at each dwelling was 3 to 5 weeks.

The original schedule for monitoring and upgrading was for all dwellings to be monitored for 12 months pre- and 12 months post- upgrading. However, due to the unexpected and deepening economic crisis in Ireland, the rate of upgrading slowed considerably. As a result the dwellings in the study were upgraded in a staggered pattern as follows:

- A, B, C and D were upgraded in 2012; and
- E, F, G, H and J were upgraded in 2013.

In both years, the upgrading took place during August when annual heating requirements should be at their lowest.

5.2.3 Cost of Upgrading

For efficiency and to get the best price based on scale the Local Authority tendered the upgrading of the dwellings in bundles of 10 – 15 dwellings. The upgrading of the study dwellings were procured in two different work packages. Based on limited information due to commercial sensitive the exact cost of each dwelling cannot be published. Table 6 outlines the estimated cost of upgrading each of the dwellings based on information provided by the local authority, local contractors and suppliers. Individual variations between dwellings were absorbed as part of the overall tendered price for the works to be completed. The average cost of upgrading the dwellings was approximately €10,000. This is similar to the findings of Curtin and Maguire (2011) who estimate the average cost of cavity-wall Insulation, attic insulation, high-efficiency boiler & heating controls and solar panels as €9,450.

Dwelling	CWI	AI	BR	SF/G S	Vent	FRD	WD	Ext	Misc	Total
	€	€	€	€	€	€	€	€	€	€
A	1100	1050	2900	1300	1200				950	8500
B	1300	1050	2900	1400	1200				950	8800
C	1300	1050	2900	1300	1200				950	8700
D	1100	1050	3500	1300	1400		2300	3700	950	15300
E	1100	1050	2900	1300	1200	880			950	9380
F	1300	1050	2900	1300	1200	880			950	9580
G	1100	1050	2900	1300	1200	880			950	9380
H	1100	1050	2900	1300	1200	880			950	9380
J	1100	1050	2900	1400	1200	880			950	9480
Average Cost										€9,833
<u>Abbreviations of upgrading measures</u>										
CWI	Cavity Wall Insulation					WD	Windows & Doors			
AI	Attic Insulation and insulating CWS					Ext	Extension			
SF/G S	Solid Fuel/Gas Insert Stoves					Vent	Ventilation - Passive and Active			
FRD	Front and Rear door					Misc.	Draught Stripping, Fire Alarm and			
BR	Boiler Replacement & Zoning, Hot water tank, Insulation to pipework and CWS						Energy Saving lighting			

Table 6 Estimated cost of upgrading individual dwellings

5.3 Monitoring System Installation and Commissioning

This section outlines the application of the data collection methodology described in Section 3.3. As detailed in the Section 1.4 the aim for the objective was to remotely gather detailed data, transfer it to a database where it would be ‘cleaned’ and presented in .php script format on a website. It was intended, that before installation, the complete system would be bench tested and calibrated at VVS Technology Headquarters. However, due to time constraints, this was not possible and individual components were produced, calibrated and installed. Installation was completed by a local contractor who was known to and procured by the researcher. Installation was scheduled for a three week period in August 2011. The majority of the installation was complete within this period. However, a number of short visits had to be made to the sites throughout September due to the incompleteness of the monitoring kits. Following installation, VVS technology was responsible for commissioning the system. The researcher was involved in the installation and commissioning of the system on a day to day basis as part of the learning process. A number of unforeseen issues arose during the commissioning phase. These are now discussed along with the implemented solutions.

Gas Meter Data Transfer

ZigBee is designed for short distance transmission of up to 100m. Figure 43a demonstrates the location of the Xemtec Comet and wireless transceiver in the meter enclosure on the external wall of the dwellings. Unexpectedly the gas meter data would not transfer wirelessly the approximate 7m through the building fabric to the DC in the attic.

Solution: The external wall of each dwelling was drilled and the transceiver relocated inside and hard wired to the Comet.

Xemtec Comet

The Xemtec Comet XRS – 60 optical reader is designed to take an image of the entire meter dial and convert the image into a digital reading. Each reader had to be individually programmed once correctly positioned. It then had to be calibrated in situ with the digits on the meter using the Xemtec Software, as shown in Figure 43a. The reader was programmed to take a reading every 15minutes and record the reading to an accuracy of 0.01m³. However, it was discovered that when operational meter digits rotated too quickly for the reader could not take an accurate reading.

Solution: All readers were reprogrammed to read to 0.1m³.

WAP Bridges

The WAP bridges required a direct line of sight to the antenna. This was not always easy and many of the set up required adjustment to go around obstructions such as trees and buildings as shown by the configuration of the polls in Figure 43 b and c.

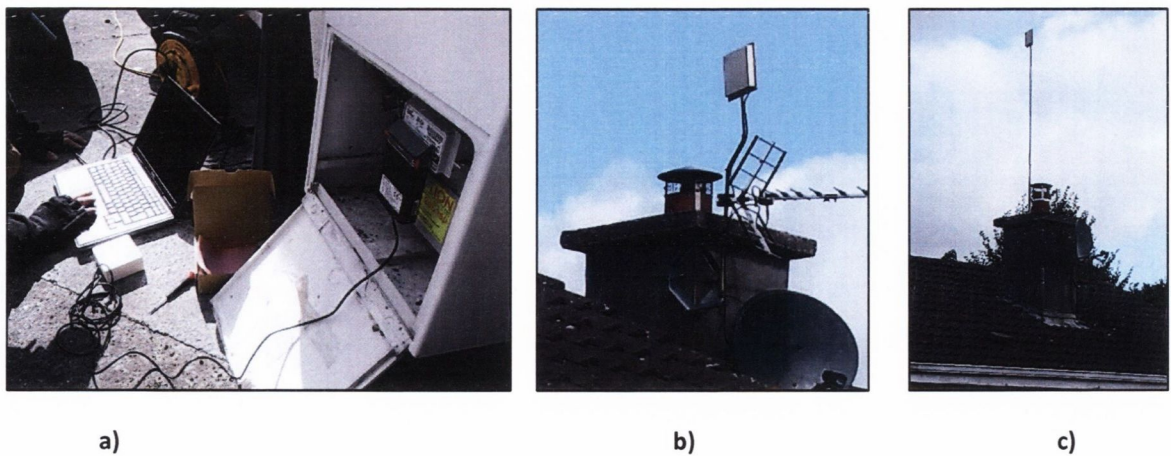


Figure 43 a) Calibration Xemtec Comet XRS – 60 optical reader b&c) WAP bridges

Occupants Prerogative

The occupants of dwellings C and F changed from their standard BK-G4 meters to Landis+Gyr Libra 200 Series prepay meters unexpectedly several months after installation was complete, as shown in Figure 44a. Post- upgrading dwelling D also opted for the prepay gas meter. The digital readout negated the ability of the Xemtec Comet to take readings. The pulse output module is used by the card reader making it very difficult to remotely take meter readings.

Dwelling E had their gas disconnected rendering the meter unusable during the monitoring and without notice. The gas remained disconnect for the remainder of the study. A prepay electricity meter was also installed, as shown in Figure 44b.



Figure 44 a) Landis+Gyr Libra 200 Series prepay meters b) Prepay electricity meter installed at Dwelling E

Calibration

Regular temperature, humidity, electricity, gas meter readings were recorded throughout the initial on-site calibration. Electricity and gas readings were taken directly from the meter on the first day of every month. Regular site visits continued between September and November 2011. There were technological problems with the systems providers which began early in the monitoring. Initially there was no access to the website but assurances were given that the raw data was being transferred correctly to the database and once corrections were established they would be applied retrospectively to correct all data. Once the website was made available in January 2012 it was evident that the system was not functioning correctly and data was being reported incorrectly. Again assurances were given that it was only correction and calibration issues and that the raw data was secure. Calibration continued until September 2012. The researcher found both the software and the support given far from satisfactory.

The researcher was thus forced to physically gather energy usage and environmental parameters in a sample of the dwellings, over a one hour period, at various times during the initial monitoring

period. Temperature and humidity readings were recorded at the remote sensor locations within the dwellings with a hand held sensor. Time and physical meter readings were taken when electricity and gas usage was being manipulated by turning on the heating and high energy usage electrical appliances. Monthly and daily total gas and electricity physical meter readings did not tally with the monitoring system. A considerable amount of time and effort was spent trying to extract consistent reliable data. Repeated analysis found that even though on the surface the data and energy use patterns seemed plausible once cross referenced with other measured parameters the system was found to be untrustworthy. Some examples include:

- The monthly totals of electric and gas usage were completely different than read directly from the meters;
- Exactly the same gas usage everyday regardless of external temperature or month;
- Sporadic electric cooker usage especially late at night. The householder was queried and said they only ever used it to cook toast for breakfast and an evening meal;
- Exactly the same temperature profiles being report in different houses;
- Temperature sensor constantly reading too high or low temperatures. Two wireless sensors in the same house when brought together still reporting completely different temperature;
- Relative humidity sensors in the kitchens reporting constant humidity even when cooking was happening.

The lesson learnt was to ensure the accuracy of any monitoring system before using assuming that which is recorded is accurate. Due in part to time constraints the complete monitoring system for each house was not correctly calibrated under laboratory conditions before installation. Consequently the relationship of the researcher with VVS Technology deteriorated considerably and came to an end.

These reliability issues with monitored energy data meant that the first heating season's data was not usable. Nonetheless, even if the system was working correctly the data would be incomplete because there were four gas meters unreadable. A complete review of the study concluded that, it was impractical to fix the problems with the existing system. With no further funding available and upgrading scheduled to commence it was not feasible to procure a new monitoring system and start the process again. The work done to date and lessons learned laid the foundation for a new strategy formulation.

Though the monitored data was undependable a significant quantity of physical information had been recorded. The new strategy required physical meter readings to be taken at regular

intervals. Physical readings were recorded for three years; at least one year pre- and post-upgrading for each of the houses. Internal temperature reading acquired by the monitoring system was unreliable and discarded. For the purpose of analysis this study used DEAP assumed internal temperatures (SEAI, 2012a).

Due to the staggered upgrading programme dwellings:

- A, B, C and D were monitored for 12 months pre- and 24 months post- upgrading; and
- E, F, G, H and J were monitored for 24 months pre- and 12 months post- upgrading.

Electricity and gas meter readings were taken in the morning of the first day of each month since the commencement of the project. Readings were also taken at 6am for 3 periods of for 7 consecutive days in November and December 2012 and March 2013.

Secondary Space Heating

Prior to upgrading each dwelling had provision for secondary space heating in the form of an open fire in the sitting room. As outlined in Section 3.3.5 solid fuel usage is difficult to monitor, particularly without influencing occupant behaviour. It was impossible to establish secondary space heating usage patterns from the thermostat above the fireplace as a result of the unreliability of the remote monitoring system.

Data on solid fuel usage was primarily gathered at pre- upgrading survey and pre- and post-upgrading interview stage. Dwelling D was the exception because pre- upgrading solid fuel was their primary heating source. In this instance, the occupants were asked to keep a weekly fuel log which was collected with the monthly readings. The logs were completed as requested. However, the researcher cannot be certain of the accuracy. In the interviews, Section 8.4, the occupants revealed that they also burned timber that they received for free. This was not quantified as part of the log. Phase 3 revealed some small anomalies with the perceived fuel use in a number of dwellings. Phase 3 found that for various reasons only dwellings C, D, E, G and H ever used their secondary space heating systems. Dwelling D used their new stove very rarely. The following briefly outlines the secondary space heating use for each dwelling:

- A: open fire never used. Post- upgrade interview noted the new stove remains unused;
- B: gas fire in sitting room not operational for years. Replaced with new gas fire but never used;
- C: open fireplace replaced with stove and used regularly throughout heating season;
- D: the main source of primary and secondary heating was provided by the solid fuel cooker located on the ground floor in the open plan kitchen-sitting room. Monthly coal

usage was recorded. It was impossible to know what other material was burned in the cooker. Sitting room fireplace rarely used. Replaced with stove which is very rarely used;

- E: open fireplace replaced with stove and used regularly throughout heating season;
- F: open fire never used. Post- upgrade interview noted the new stove remains unused;
- G: open fireplace replaced with stove and used regularly throughout heating season;
- H: open fireplace replaced with stove and used regularly throughout heating season;
- J: Gas fire in sitting room blocked off for years. Replaced with new gas fire but never used.

From the interviews it was deduced that the occupants consume similar volumes of solid fuel as before but the efficiency of the stoves in use resulted in a change in behaviour.

5.4 Conclusion

This chapter presented the works primarily undertaken for phase one and two of the study. The chapter discusses the challenges involved in executing extensive selection process for the dwellings. The chapter outlined the implementation process for the monitoring equipment. The design, installation and commissioning of a bespoke energy monitoring system is a complex process and relies on the convergence of a number of variables. This chapter outlined the information gathered through the interviews relating to the chapter concludes by dealing with solid fuel use. The chapter again highlights the difficulty when attempting to gather solid fuel use. The challenges of designing bespoke energy monitoring systems were large. Many were overcome but ultimately the system did not perform as designed. The researcher found this aspect of the study to be a massive learning opportunity.

Chapter 6

6 Quantitative Results and Analysis – Effectiveness of Upgrading with Respect of Energy Consumption

6.1 Introduction

This chapter presents the results of the 36 month longitudinal monitoring study. The main aim is to present a multi-level quantitative analysis that assesses the effect of energy efficient upgrading on theoretical and real energy use. The chapter outlines the development of the analytical approach taken to establish the dwellings electricity and SWH energy load profiles, taking climate variables into account. The chapter also presents the findings of the quantitative analysis and evaluates the scale of the energy savings. The chapter addresses objective 3 by comparing the monitored results with DEAP predicted performance and establishes the real energy savings taking climate variables into account. Maintaining the principles of the TBL the energy savings are assessed in terms return on investment.

6.2 DEAP Analysis

DEAP gives an estimate of energy performance of the building under standard occupancy and usage patterns. However, as Irelands National Methodology for calculation the energy performance and verification tool for SHIP it was considered important to evaluate its exactness when predicting energy savings. BER's and airtightness tests were completed over the summer periods pre- and repeated post- the upgrading works being completed. The pre- upgrading BER's surveys took approximately two hours to complete. This was followed by two hours' work inputting the data to the DEAP software and calculating the BER's. The post upgrading BER's took half the time using the pre- upgrading surveys as a template. airtightness test took approximately four hours to complete.

DEAP generated BER certificates present the summation of primary energy required for space heating, ventilation, water heating and lighting, less savings from energy generation technologies. Figure 45 presents the results of the pre- and post- upgrading BER's used to verify savings made in accordance with the requirements of SHIP. BER's were calculated using the DEAP assumptions for 'structural airtightness' followed by the inclusion of the actual airtightness tests results. The effect of upgrading on airtightness is assessed in detail in Chapter 7.

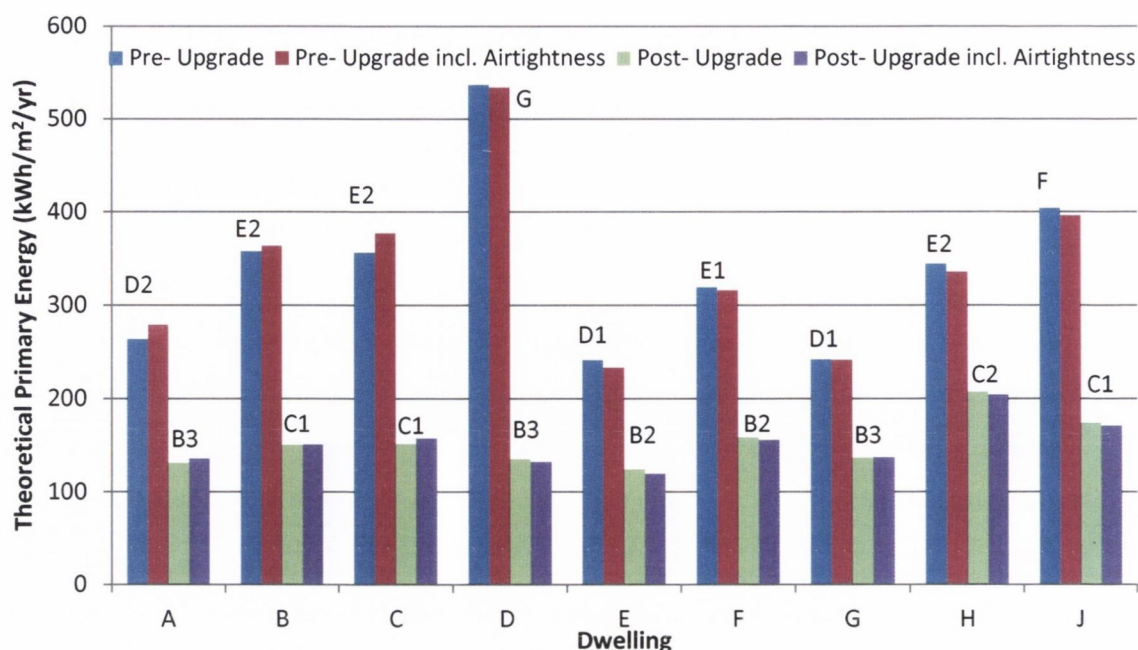


Figure 45 Pre- and post-upgrading BER's

	A	B	C	D	E	F	G	H	J
BER									
kWh/m ² /yr	132	208	205	402	117	161	105	138	230
%	50	58	57	75	49	50	44	40	57
BER including Airtightness Results									
kWh/m ² /yr	144	213	220	402	114	160	105	132	225
%	51	59	58	75	49	51	43	39	57

Table 7 DEAP calculated theoretical energy savings

There is a large variation in predicated performances from 240 to 537 kWh/m²/yr, considering that superficially the dwelling characteristics and ages are relatively uniform. From Table 7 it is clear that including airtightness results have a nominal impact on final BER's. There is a typical expected improvement in energy performance of 40 to 58%. Dwelling D is an outlier with an expected saving of 75%. This is primarily as a result of upgrading the solid fuel heating system to a gas boiler and controlled zones.

Comparison with monitored data

Assessing DEAP calculated BER's and monitored consumption is not a like for like comparison. DEAP does not attempt to calculate all electrical loads in dwellings. The DEAP software calculates the equivalent delivered energy in addition to primary energy consumption, which discounts the energy loss in the generation, transmission, and distribution of energy. This delivered energy is the consumption that normally appears on the customer's energy bill. The primary space heating system also provides hot water in the dwellings. Pre-upgrading, the limited system controls

meant that space and water heating occurred simultaneously. It was intended that the hot water monitoring system would be used to independently calculate the energy used to heat the water. It was impossible to separate the energy requirements since the monitoring system did not work effectively. Hence, in this study gas consumption refers to primary space and water heating (SWH). To ensure like for like comparison the DEAP predicted energy consumption for the SWH were extracted from the DEAP results.

A conversion factor was applied to establish delivered energy (kWh) from the meter readings (m^3). The conversion factor is constantly changing as the energy content of the gas is dynamic. This is continually monitored by the energy supplier and published in the bi-monthly billing. The bi-monthly conversion factor (cf) was recorded from these bills throughout the study. There was a relatively small variability in the energy value of the gas throughout the duration of the study. Thus, a single Conversion Factor (CF) was established by:

$$CF = \frac{1}{n} \sum_{i=1}^n cf_i \quad \text{Equation 10}$$

For this study the gas conversion factor was established to be 11.339 i.e. $1m^3 = 11.399kWh$.

Note: Dwelling D is an exception in this case because pre-upgrading SWH and secondary heating were provided by a solid fuel cooker in the kitchen. A CF was applied to the quantity of solid fuel used to estimate annual kWh energy use. The CF for coal of 1Tonne = 7734kWh (SEAI, 2014).

Total gas consumption for dwellings B and G should include the volume used for the gas fireplace room heaters. However, neither system was in use throughout the study and omitted from the calculations.

Figure 46 presents the comparison of measured energy and theoretical energy consumption pre-upgrading for SWH. The theoretical energy consumption excludes airtightness results. The real measured energy consumption ranged from 43% to 116% with a mean 60% of the theoretical energy predicted by DEAP for the nine dwellings. Dwelling J is an outlier as this is the only dwelling to exceed the theoretical consumption using 116% of the predicted energy use. Dwelling H, which has almost identical physical parameters used just 81% of that predicted. For Dwelling D DEAP the estimated solid fuel usage was 100% more than was actually consumed.

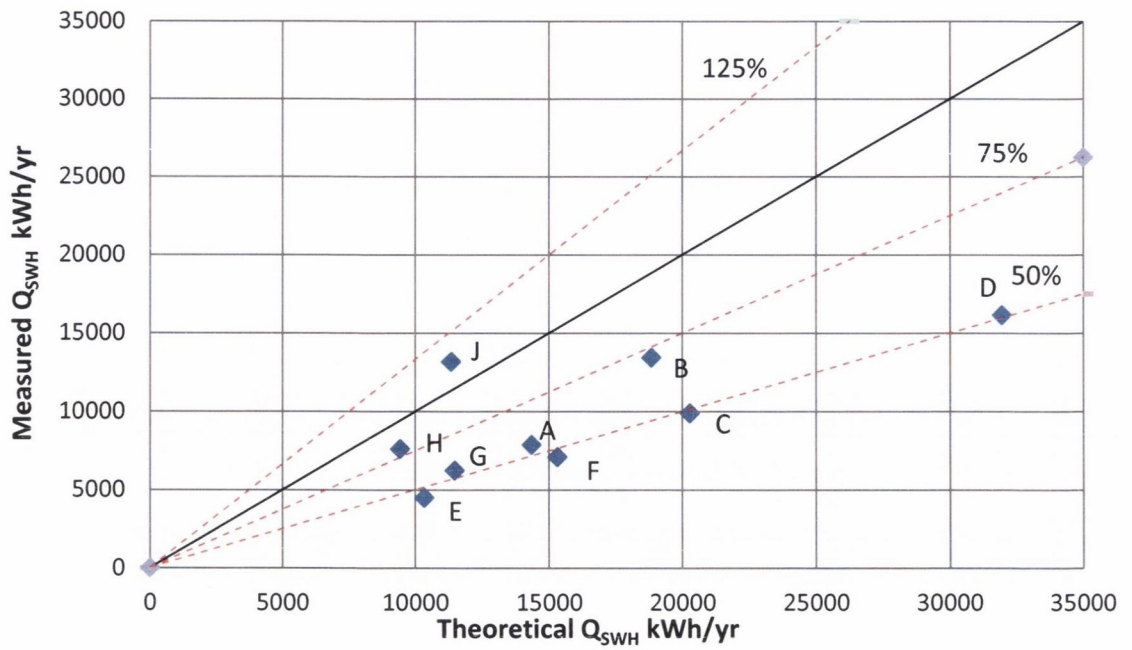


Figure 46 Pre- Upgrading Measured versus Theoretical Delivered Space and Water Heating Energy Consumption

Post- upgrading results presented in Figure 47 demonstrate greater variations between measured and theoretical energy performance ranging from just 23% to 143% and mean 71.6% of that predicted by DEAP. Dwelling J remains the highest energy consumer whilst dwellings G, H & F at circa 25% are using considerably less energy than predicted by DEAP and have also reduced their actual consumption considerably. Post- upgrade results for Dwelling E were not deemed useable for inclusion as the gas supply was terminated just before upgrading.

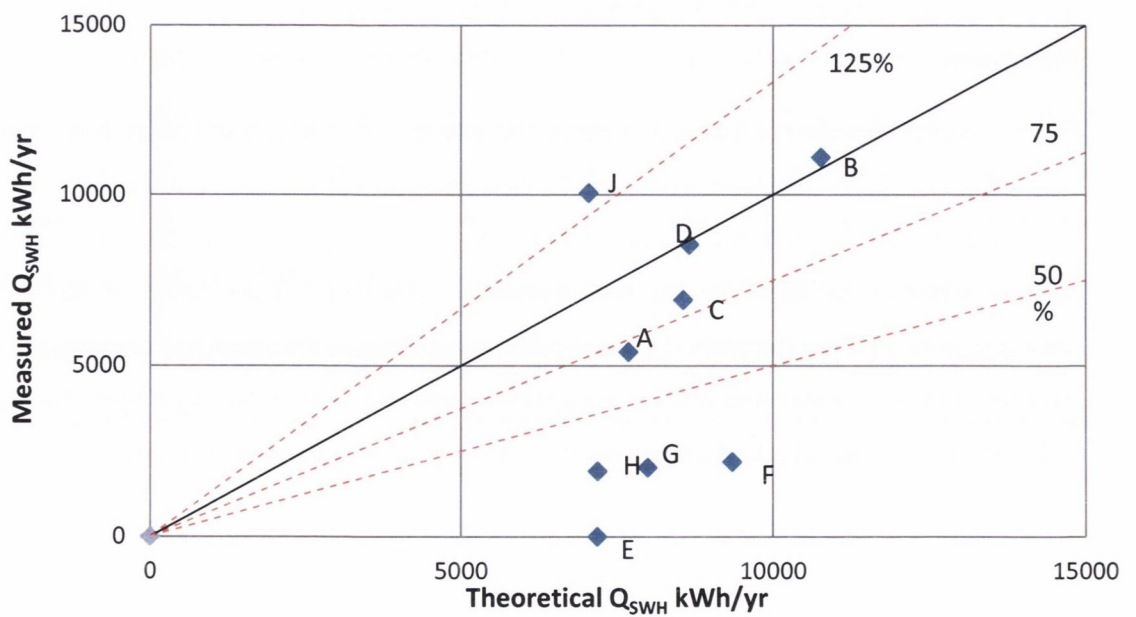


Figure 47 Post- Upgrading Measured versus Theoretical delivered energy consumption for space and water heating

Consideration needs to be given to the limiting processes that DEAP uses in its calculations. DEAP acknowledges that *“the energy consumption patterns of real occupants vary widely”* (SEAI, 2012b p. 42). However, DEAP calculates performance independent of the individual characteristics and uses standardised assumptions relating to occupancy, and heating parameters. Therefore at best DEAP can only give an estimate of real energy performance.

Pre- and post- upgrading DEAP overestimated SWH energy consumption by an average 40% and 28% respectively. Some potential reasons for these results include:

- Households do not heat their homes to the level anticipated by the DEAP software. DEAP assumes a ‘Heating Schedule’ from October to May inclusive to maintain the set-point internal temperatures in the living area of 21°C and 18 °C for the rest of the building as 07.00 to 09.00 and 17.00 to 23.00. This standardised regime equates to a total 56 hour weekly heating period. It could be expected that dwellings would be heated for shorter periods in social housing because they are a greater risk of fuel poverty. Post- upgrading, it is easier to heat the house and it can be assumed that comfort levels increased thus the house would be heated to a higher level i.e. closer to the temperatures that DEAP predicts.
- DEAP defaults for physical parameters are conservative where exact details from inspection are not available. This is a particular issue when assessing existing dwellings.
- DEAP assumes a standardised occupancy. The definition for standardised occupancy is not provided in the DEAP software manual, but may be assumed to the national average 2.8 persons. Though there is no obvious correlation with occupancy across the board it could have a bearing.
- DEAP establishes Boiler efficiency from the HARP Database. It is difficult to predict the actual seasonal efficiency of each individual boiler without testing each system.
- DEAP applies utilisation factors to heat gain calculations in apportion only a part of the total gains that contribute to internal temperatures. These factors may not be appropriate for specific Irish conditions.
- DEAP calculates energy consumption based on mean national climate parameters. Therefore, local and annual climate variation was no accounted for in the calculations.

Section 6.2 does not provide an in-depth analysis of the DEAP assessment criteria but highlights the trade-off between accuracy and simplified calculation procedure.

Though DEAP results may be representative of national domestic energy use the model is inaccurate at a micro level leading a performance gap and cynicism amongst occupants about the usefulness of the methodology.

Energy consumption is affected by many factors in addition to the physical building parameters. For example, occupant behaviour including 'take back' following upgrading, and socio-demographical characteristics, such as income, age and occupancy patterns. However, the level at which each of these factors can be attributed to energy usage is little understood and difficult to determine. Irish energy policy is based around achieving energy saving targets. However, without a clear understanding of how to achieve these savings the performance gap cannot be bridged. This section highlights the need for a more in-depth study to understand the drivers for real energy use in social housing in Ireland.

6.3 Monitored consumption - initial observations

Figure 50 and Figure 51 present the raw recorded monthly SWH and electricity energy consumption for the nine dwellings. Initial observations reveal a divergence between SWH and electricity usage patterns throughout each year. As expected pre- and post- upgrading gas consumption increased over the winter periods and bares a correlation with Heating Degree Days (HDD). It is notable that post- upgrading over the 2013/14 heating season dwellings F, G and H SWH consumption do not correlate as well as prior to upgrading. A different trend is evident for electricity usage which seems to peak and trough on a monthly basis and observationally does not correlate well with external climate conditions.

There is a notable difference in energy use patterns between the dwellings even though they are of a homogeneous building type. An explanation for this is not obviously apparent from the data. As presented in its raw form it is difficult to tell if the variability can be attributed to floor area or some other physical parameters.

Figure 50, Figure 51 and Figure 52 present the annual SWH, electricity and combined consumption for the dwellings pre- and post- upgrading. It is clear that there are some SWH energy savings as a result of the upgrading. However, where two years pre- or post- are compared there are noticeable differences in consumption. In this case it is evident that direct year on year comparison of results is not suitable to quantify savings because it does not take climate variables into account. Therefore, it is necessary to normalise the data taking these variables into account. Section 6.4 presents the methodology used to normalise the consumption data.

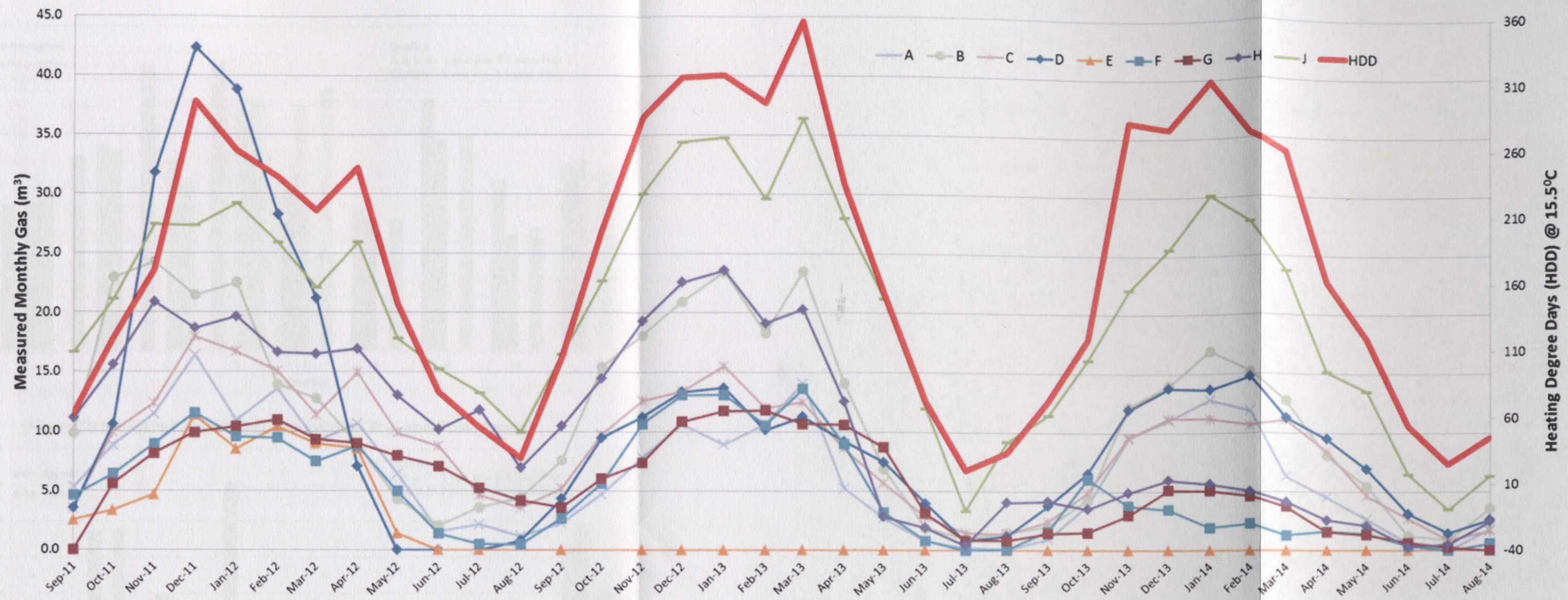


Figure 48 Measured Monthly SWH Consumption and Correlated Heating Degree Days

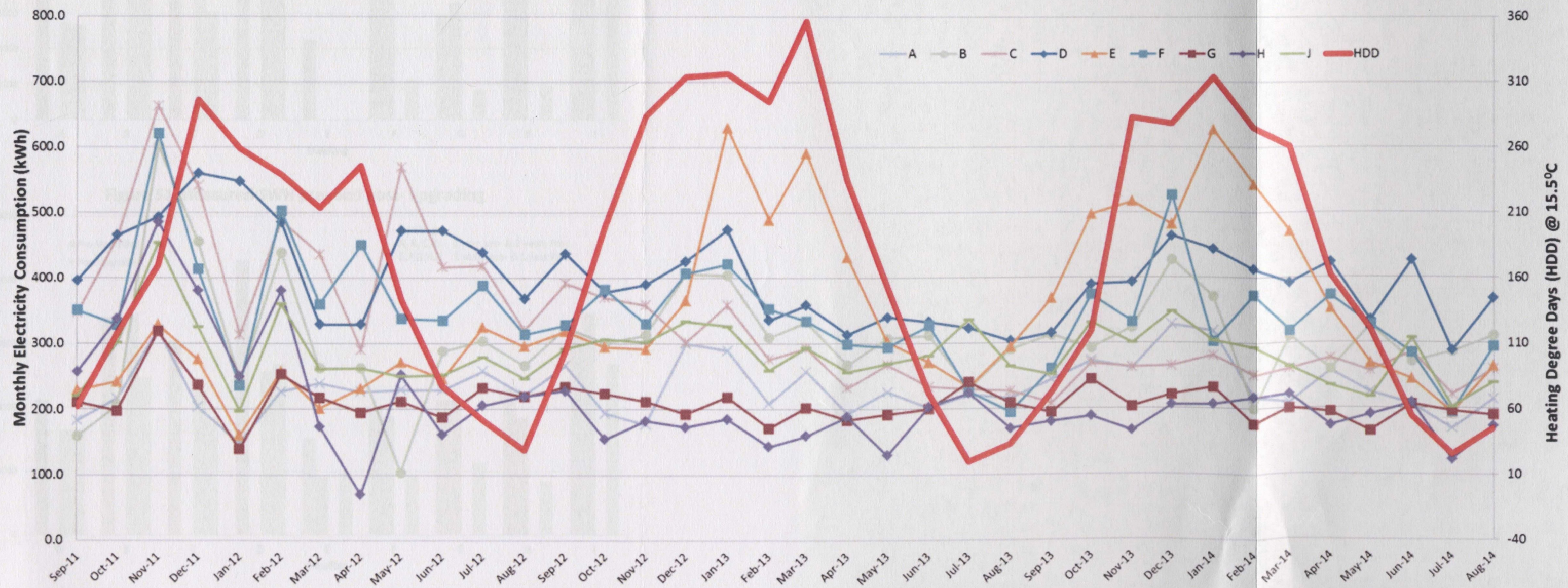


Figure 49 Measured Monthly Electricity Consumption and Correlated Heating Degree Days

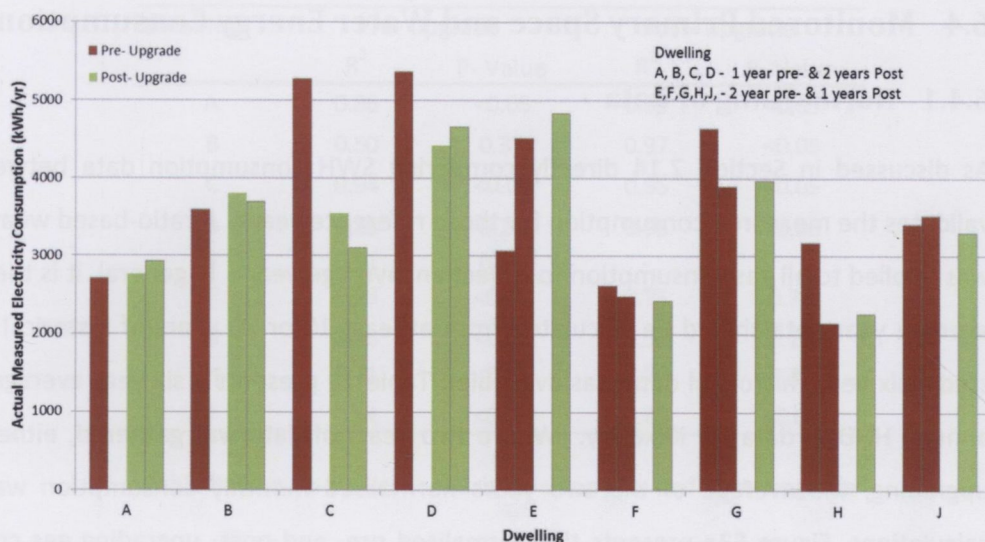


Figure 50 Measured Electricity Consumption Pre- and Post- Retrofit

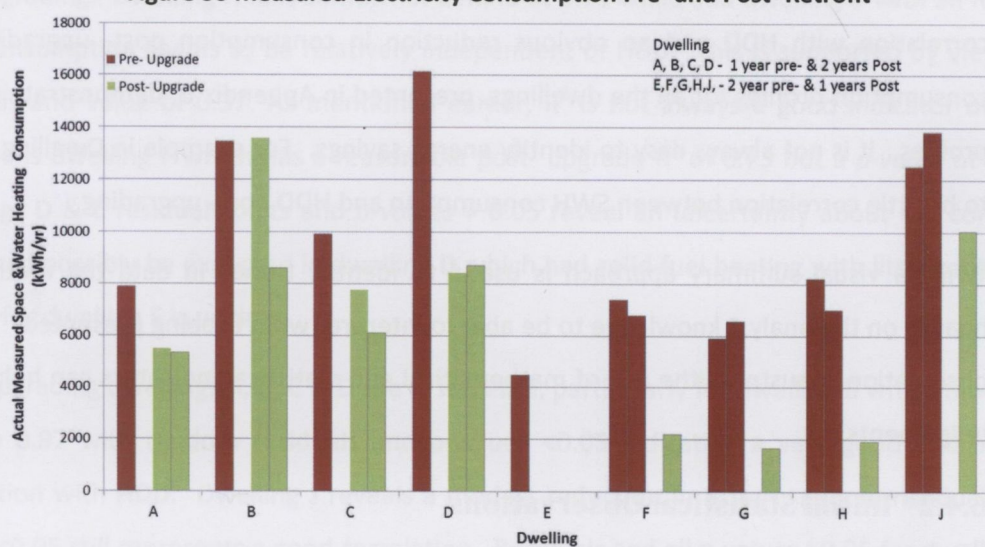


Figure 51 Measured SWH pre- and post-upgrading

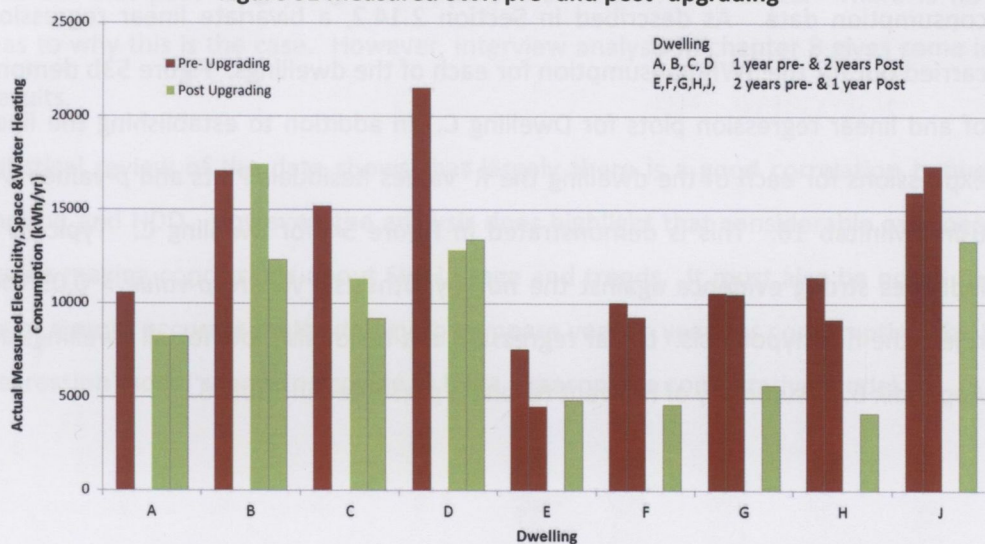


Figure 52 Measured combined electricity and SWH pre- and post-upgrading

6.4 Monitored Primary Space and Water Energy Consumption

6.4.1 Normalising of Data

As discussed in Section 2.14 directly comparing SWH consumption data between years only validates the measured consumption for those reference years. A ratio-based weather correction was applied to all gas consumption to reflect an 'average year'. In general, it is accepted that average year data should be calculated from at least 10 or 20 years of historical data. For this study, six years historical data was available. Table 10 presents a six year average, monthly and annual, HDD_{15.5} data for Kilkenny. Where two years of data was gathered, either pre- or post-upgrading, the average of the two years normalised monthly consumption was used in the calculations. Figure 53a presents the normalised pre- and post-upgrading gas consumption for Dwelling C, as a typical example of one of the dwellings. Visually there seems to be a good correlation with HDD and an obvious reduction in consumption post-upgrading. The SWH consumption profiles for all the dwellings, presented in Appendix B, demonstrate different usage profiles. It is not always easy to identify energy savings. For example in Dwelling D there seems to be little correlation between SWH consumption and HDD post-upgrading.

While a visual summary approach is useful to identify trends in data the methodology relies heavily on the analyst knowledge to be able to interpret what is being presented. To improve the observation robustness the use of mathematical and statistical indicators can help to inform the judgements.

6.4.2 Initial Statistical Observations

It was important to validate the data observations before making any conclusions about the consumption data. As described in Section 2.14.2, a bivariate linear regression analysis was carried out for the SWH consumption for each of the dwellings. Figure 53b demonstrates one set of and linear regression plots for Dwelling C. In addition to establishing the linear relationship expressions for each of the dwelling the R^2 values Residuals Plots and p -values were established using Minitab 16. This is demonstrated in Figure 54 for dwelling C. Typically p -value ≤ 0.05 indicates strong evidence against the null hypothesis. Where p -value > 0.05 the study fails to reject the null hypothesis. Linear regression and residuals plots for all dwellings are presented in Appendix B. A summary of relevant results is presented in Table 8.

Dwelling	Pre- Upgrade		Post- Upgrade	
	R ²	P- Value	R ²	P- Value
A	0.86	<0.05	0.95	<0.05
B	0.50	0.37	0.97	<0.05
C	0.94	<0.05	0.95	<0.05
D	0.86	0.24	0.95	<0.05
E	0.91	0.50	-	-
F	0.79	<0.05	0.75	0.70
G	0.93	<0.05	0.55	0.29
H	0.71	<0.05	0.70	0.37
J	0.94	<0.05	0.85	<0.05

Table 8 R² and *p-values* for each dwelling pre- and post- upgrade

Seven dwellings have an R² of between 0.79 and 0.94 representing a reasonable to very good fit pre- upgrading. Dwelling H falls somewhat behind at 0.71 while and dwelling B with an R² of 0.50 SWH consumption seems to be relatively independent of HDD. This is supported by viewing the residuals and value of 0.37. As mentioned earlier, R² is not always a good indicator of fit. An example is dwelling F which has a reasonable post- upgrade R² of 0.75 but a *p-value* of 0.7. For dwellings D & E residuals plots and *p-values* > 0.05 reveal an uncertainty about the correlation. This could possibly be expected in dwelling D which had solid fuel heating with little control. The reason for dwelling E is unclear.

Post- upgrading dwellings A, B, C & D see R² increase, particularly for dwelling B which moves from 0.50 to 0.97 with random residuals and *p-values* <0.05 indicating a very good and increased correlation with HDD. Dwelling J reveals a modest reduction in R² but random residuals and *p-values* <0.05 still represents a good correlation. Residuals and all *p-values* >0.05 for dwellings F, G and H reveal that post- upgrading that apparent correlation decreases. There is no obvious reason as to why this is the case. However, interview analysis in chapter 8 gives some insight to these results.

This statistical review of the data shows that largely there is a good correlation between SWH consumption and HDD. However, the analysis does highlight that considerable care needs to be taken when making conclusions about SWH usage and trends. It must also be noted that in the absence of a more accurate methodology to compare year to year gas consumption the bivariate linear regression model seems to provide at least a reasonable comparative model.

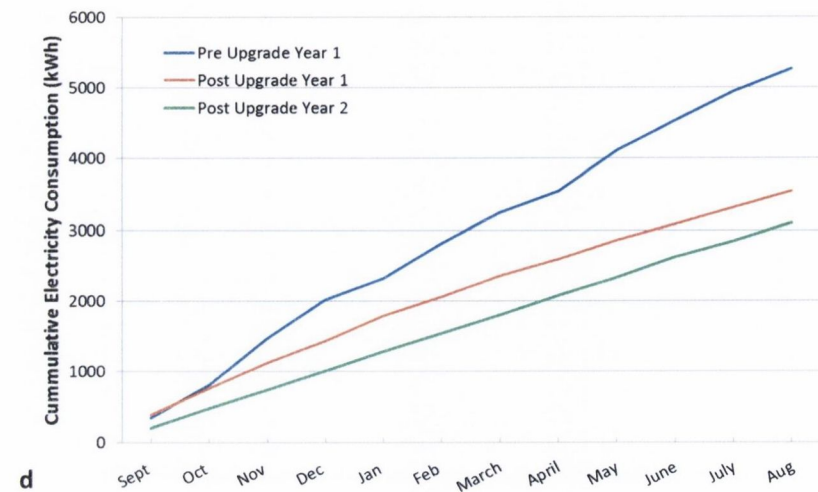
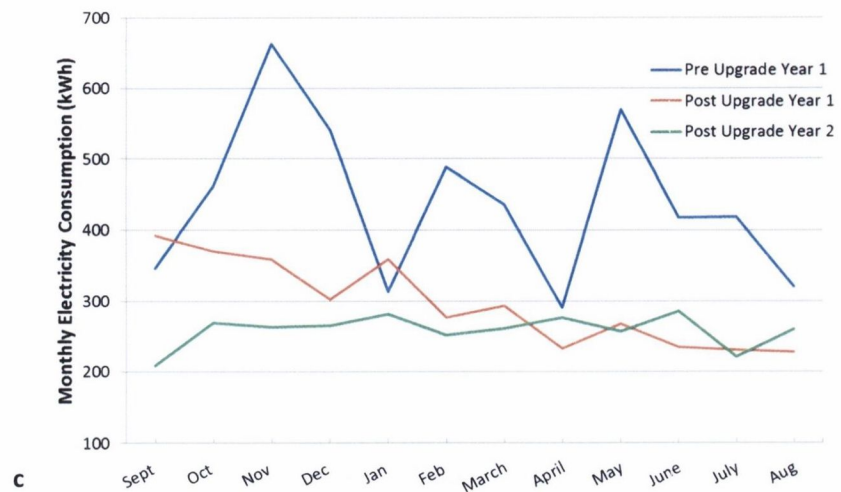
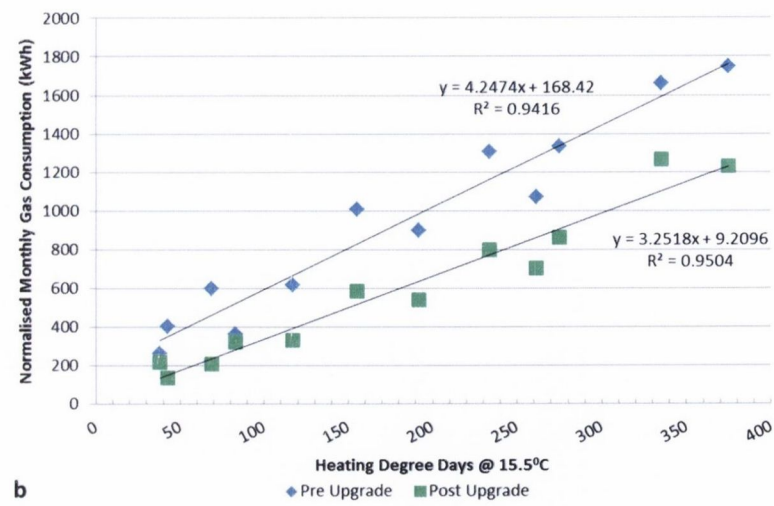
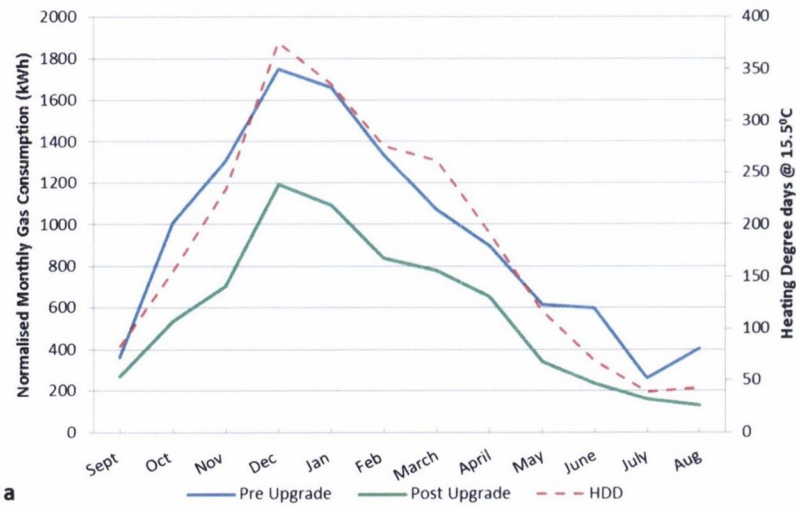
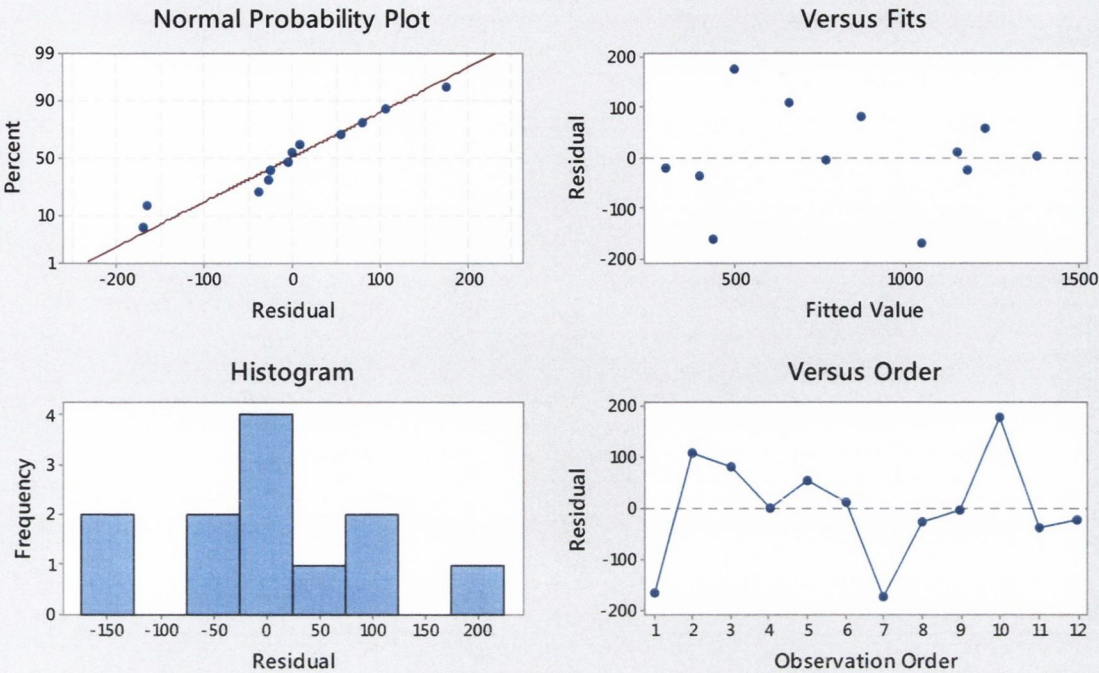


Figure 53 Dwelling C SWH and Electricity Consumption

Gas Usage Residual Plots for Dwelling C Pre- Upgrade



Gas Usage Residual Plots for Dwelling C Post- Upgrade

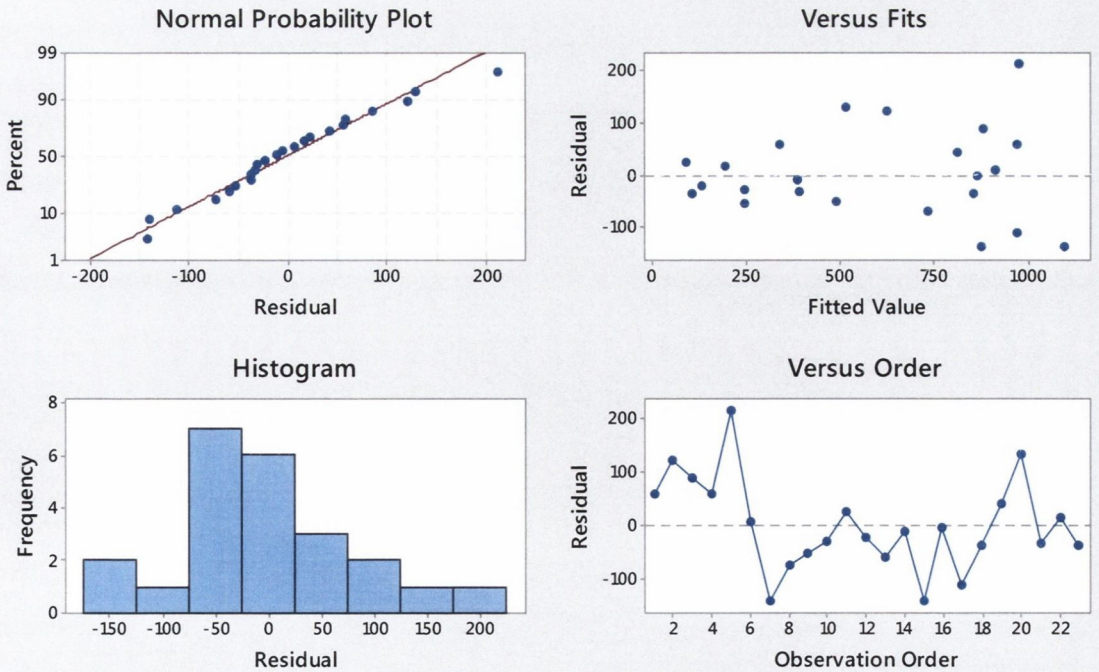


Figure 54 Dwelling C pre- and post- upgrading residuals plots

Baseload Calculation

Section 2.14.3 outlines two methodologies which in theory can be used to establish the weather independent baseload. Assuming the occupant's inter-annual hot water use remains consistent it is reasonable to assume that the baseload for each of the dwellings would be similar pre- and post- upgrading. Some baseload reduction may be observed as a result of the efficiency gains by replacing the boiler.

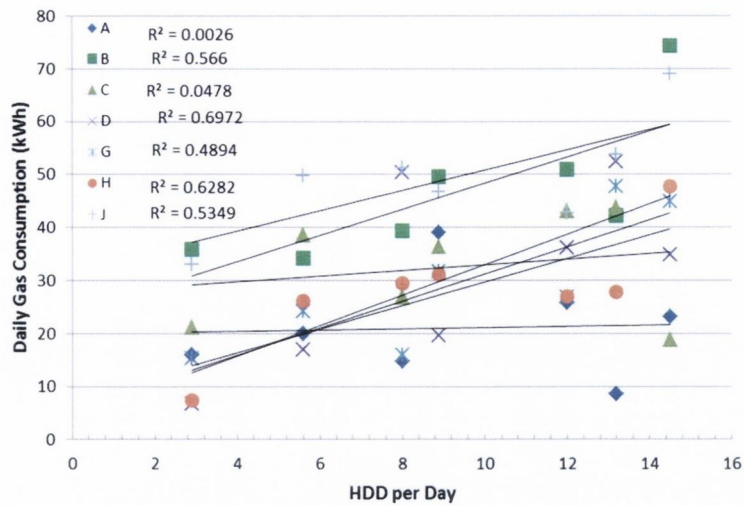
Reviewing the linear regression plots, as presented in Appendix B, for each dwelling in many cases the intercept pre- and post- upgrading are vastly different and in a number of cases the intercept particularly post- upgrade is negative. This may indicate that the base temperature is incorrect. However, a number of iterations at variable base temperatures did not reveal any discernible improvement.

Extrapolating summer heat load annually is also difficult as all dwelling demonstrate that the heat load varies over the summer period and choice of baseload would be somewhat subjective. Occupants can turn on heating for a short period if they feel cold at any time during the year which is not case in commercial buildings. The baseload is so dependent on base temperature as pre- upgrading, the heating systems heated both water and space heating simultaneously it was decided to include the baseload energy requirement in the calculations.

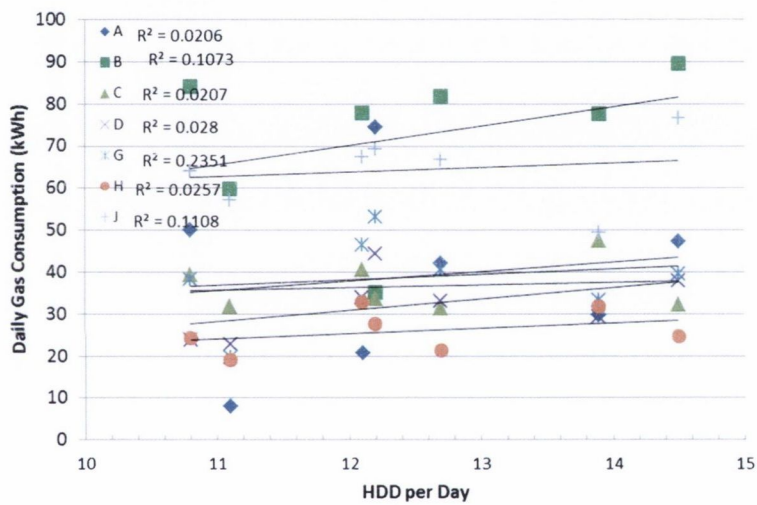
There are inherent uncertainties in both methodologies particularly for dwellings and reality baseload is variable throughout the year. Therefore, it is easier to deal with gas consumption as a whole dwelling energy consumption rather than weather dependant and weather independent.

Notable uncertainties

Daily gas consumption readings were taken at different periods during the study. Figure 55 demonstrates and attempts to carry out a linear regression analysis on daily recorded data over two weeks in November and March. Plotting R^2 for degree day days reveals R^2 of between 0.02 and 0.62. This supports Day and Karayiannis (1999), saying that HDD days are only suitable for analysis over longer periods. The results indicate that not just external climate conditions affect energy use and that occupant activity has a large bearing on inter-day energy consumption.



a)



b)

Figure 55 Gas consumption versus HDD days linear regression for a) November 19th – 25th 2012 and b) March 27th – April 3rd

6.5 SWH consumption results

Section 6.4 showed that there is generally a good correlation between the SWH and HDD. Hence, weather normalisation of SWH consumption is a reasonable methodology to allow for inter-annual SWH consumption analysis. Figure 56 presents the results of the normalised annual SWH consumption pre- and post- retrofit for each dwelling. It is clear that there is a large variability in SWH consumption between dwellings that have very similar physical and occupant characteristics. Pre- upgrading the SWH consumption ranged from 35 to 273 kWh/m²/yr. The average normalised SWH consumption was 148kWh/m²/yr compared to the DEAP calculated 213kWh/m²/yr. This was 30% less than predicted.

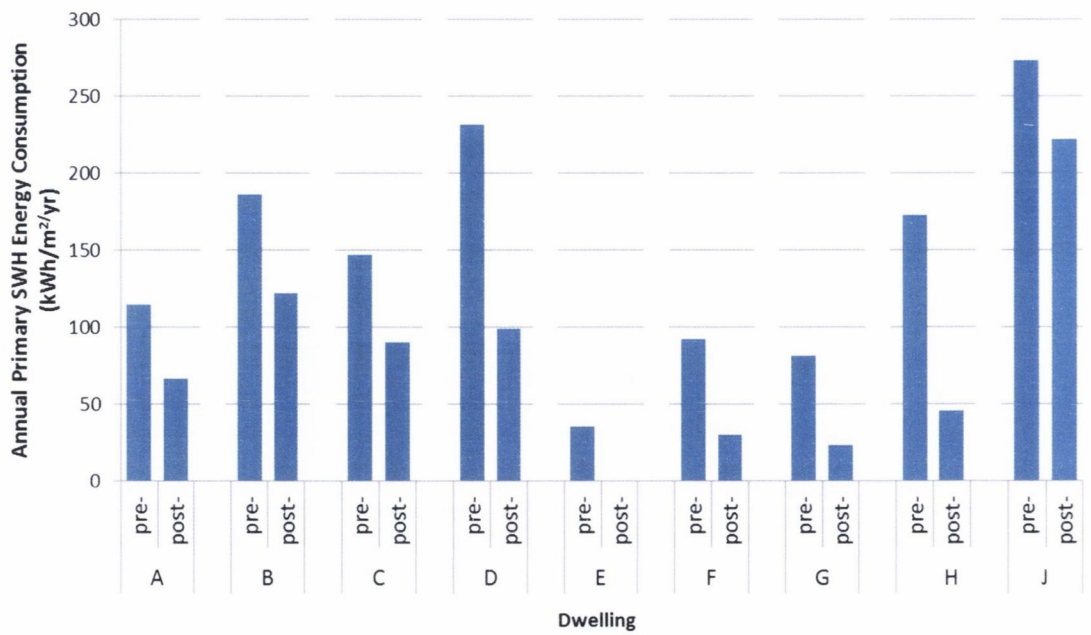


Figure 56 Gas Consumption pre- and post- upgrading

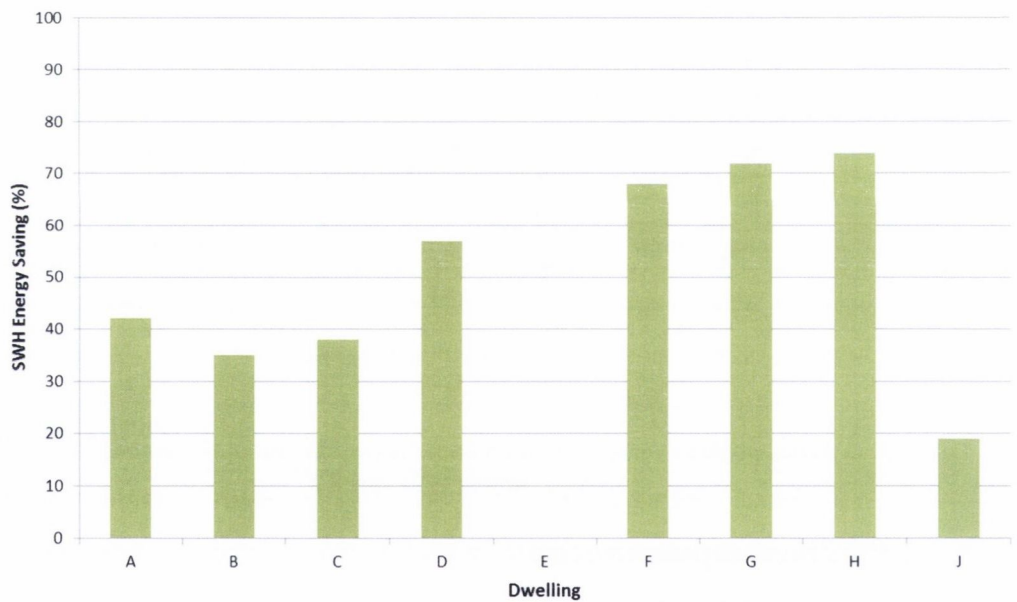


Figure 57 Proportional SWH energy savings

Figure 57 demonstrates the range of proportional energy savings from 19 to 72%. Excluding dwelling E the average SWH savings are 47%.

Electricity consumption results Figure 49 and Figure 58 demonstrate the large variability in month to month consumption throughout the year. Observational analysis and a basic linear regression of electricity consumption indicated that monthly electricity consumption for eight of the nine dwellings pre- and post- upgrading was stochastic in nature with no notable correlation with HDDs. This supports the work of McLoughlin *et al.*, (2012) who concluded that electricity

consumption patterns for domestic dwellings are highly stochastic, often changing considerably between customers. The only exception was dwelling E post- upgrading which relies on electric heaters for space heating. A further example of this stochastic behaviour is demonstrated in Figure 53c where there is no obviously apparent reason why the pre- upgrade electrical consumption in the January is substantially less than for December and February of the same year. Taking these factors into account, normalisation of the monthly electrical consumption data would not be useful.

Pre- upgrading, the average monthly electricity consumption ranged from 2.8 to 5.8kWh/m². Comparing energy consumption in terms of number of occupants rather than floor area yields still demonstrates the large variability in monthly average consumption. For example dwelling G, with an adult and two children, use an average 213kWh per month while dwelling H, with a single occupant, use 222kWh.

Figure 59 and Figure 60 presents pre- and post- upgrading annual electricity consumption and proportional energy savings. Average dwelling electricity consumption reduced by a marginal 7.5% post- upgrading. Dwellings A and B have seen a nominal increase in consumption. There is no obvious reason for this increase. Dwelling E, which had the gas supply terminated, now uses electric room heaters to heat the house. This has resulted in a 27% increase in electricity consumption. However, overall their electricity consumption is still similar to many other dwellings. Omitting dwelling E, the average reduction in electricity consumption increases to 12%. Dwelling C had the largest reduction of 37%. Revealed in the interview, Section 8.3, a probable reason was the installation of a prepay electricity meter at the time of upgrading which has seen the occupants become more energy conscious.

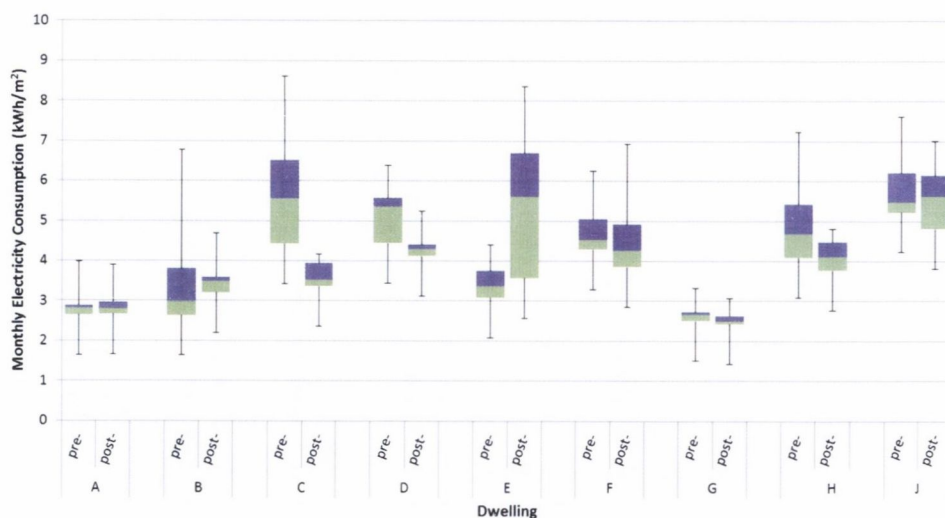


Figure 58 Monthly Electricity Consumption (kWh/m²) Pre- and Post-Upgrading

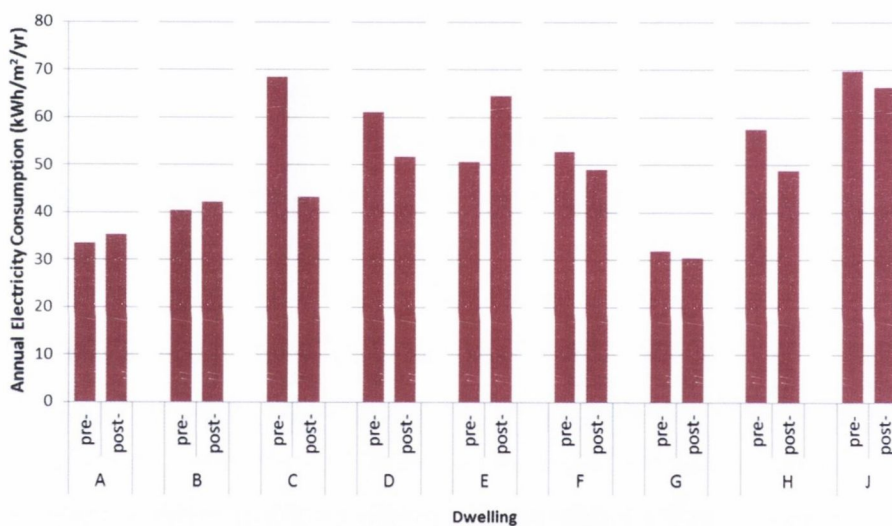


Figure 59 Annual Electricity Consumption (kWh/m²) pre- and post-upgrading

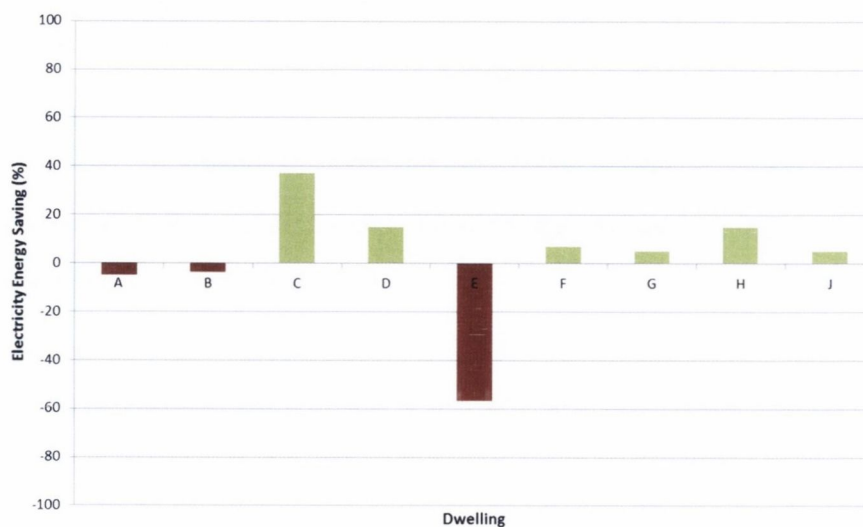


Figure 60 Proportional electricity energy savings

6.6 Combined SWH and Electricity Consumption

Figure 61 presents the combined annual SWH and electricity consumption for each of the nine dwellings pre- and post- upgrading. Figure 62 presents the proportional energy savings as a result of the upgrading. Initial observations show that there is considerable variation in the consumption patterns of all the dwellings. Total consumption pre- upgrading ranges from 86, dwelling E, to 343kWh/m²/yr for dwelling J. The average pre- and post- combined energy consumption is 200 and 133 kWh/m²/yr respectively. This represents an average annual saving of 33%.

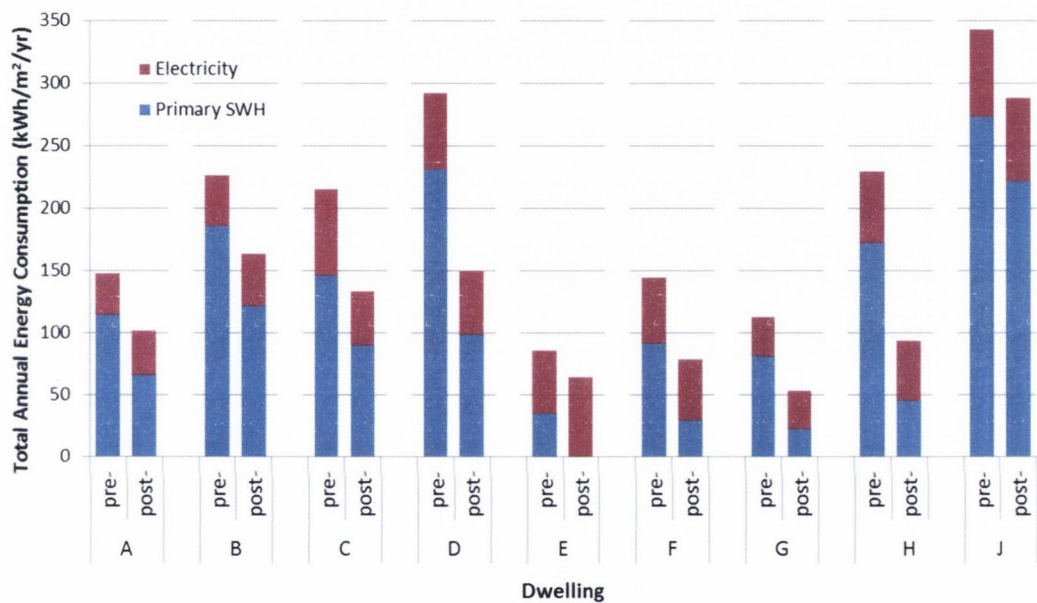


Figure 61 Combined SWH and electricity consumption pre- and post- upgrading

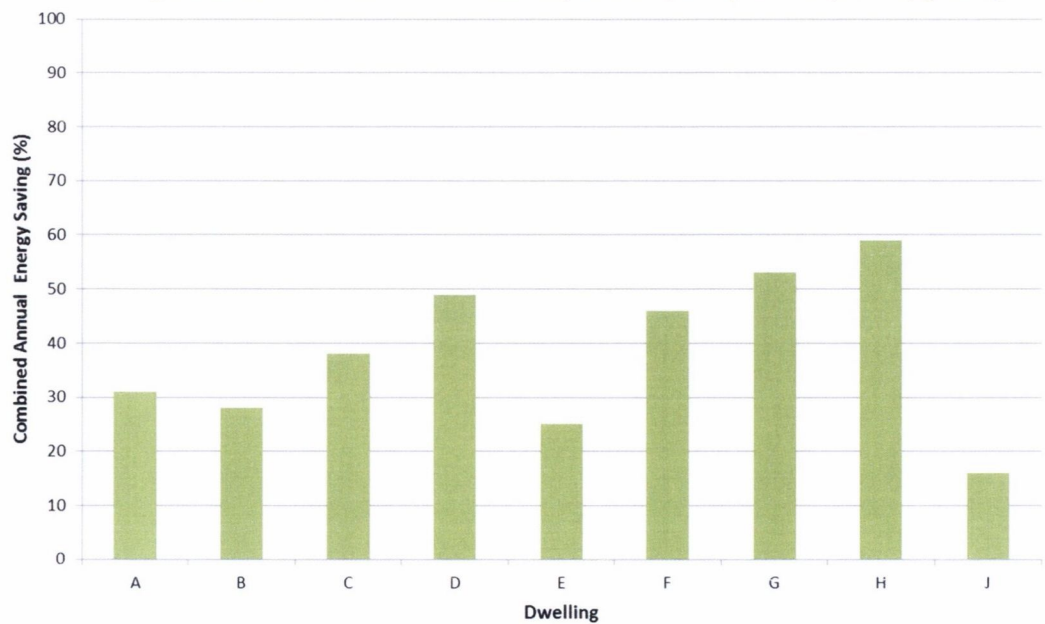


Figure 62 Proportional combined annual energy savings

Article 4 of the recast EPBD states that when upgrading the building envelope the level of upgrading should be set “with a view to achieving cost-optimal levels” (European Parliament, 2010 p. 153/19). As outlined in Section 3.1 this study embraces the TBL concept. The economic benefit of the upgrading is assessed in Table 9, based on residential average tariff, including all taxes, energy prices published by SEAI (Howley *et al.*, 2013). For dwelling D the pre- upgrading cost was based on the actual price the occupants paid for their coal.

	A	B	C	D	E	F	G	H	J
Pre- upgrading (€)	1223	1905	1945	2212	899	1466	1008	1130	1682
Post- upgrading (€)	1003	1569	1215	1605	1112	1069	677	656	1477
Annual Saving (€)	220	336	729	606	-213	396	331	473	206

Table 9 Total annual cost of SWH and electricity consumption for a typical year

Though dwelling E did see an overall reduction in their energy consumption because of the cost per kWh of electricity is almost 3.5 times that of gas the occupants are financially worse off. Excluding dwelling E, the average saving per dwelling is approximately €410. Based on the LA spending of just over €10,000 per dwelling the average payback is approximately 24 years.

6.7 Energy Consumption Correlations

The physical parameters of nine dwellings in this study may be described as homogenous in the context of all dwelling types in Ireland. However, within the sample there is variability in terms of floor area, number of storeys, occupant profile and household income. Figure 63, Figure 64 and Figure 65 demonstrate attempts to characterise the energy consumption by comparing SWH and total annual consumption pre- and post- upgrading with number of occupants, total household income and income per adult, internal volume and exposed envelope area.

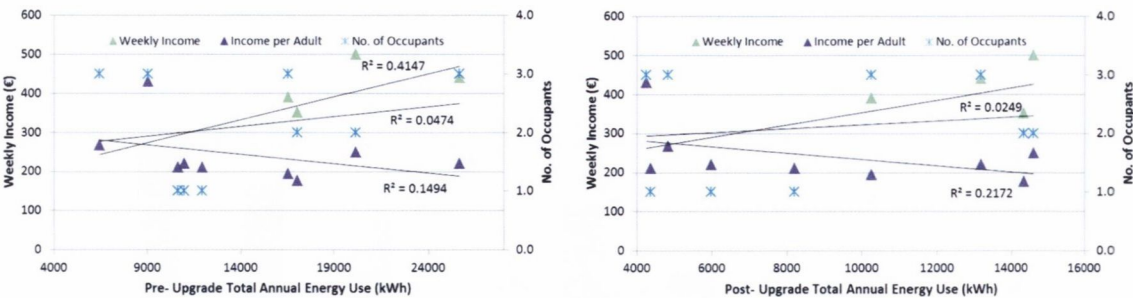


Figure 63 Total Energy Consumption Comparison Pre- and Post- Upgrading for Total Income, Income per adult and Number of Occupants

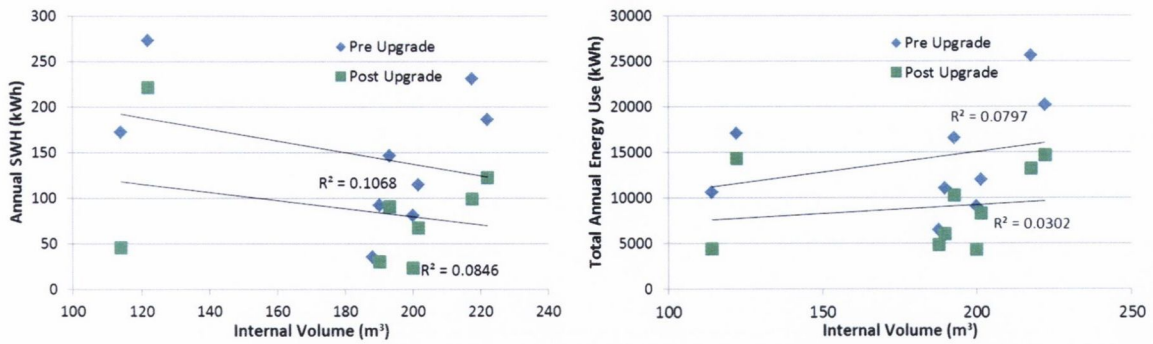


Figure 64 Annual SWH and Total Energy Consumption comparison with Internal Volume

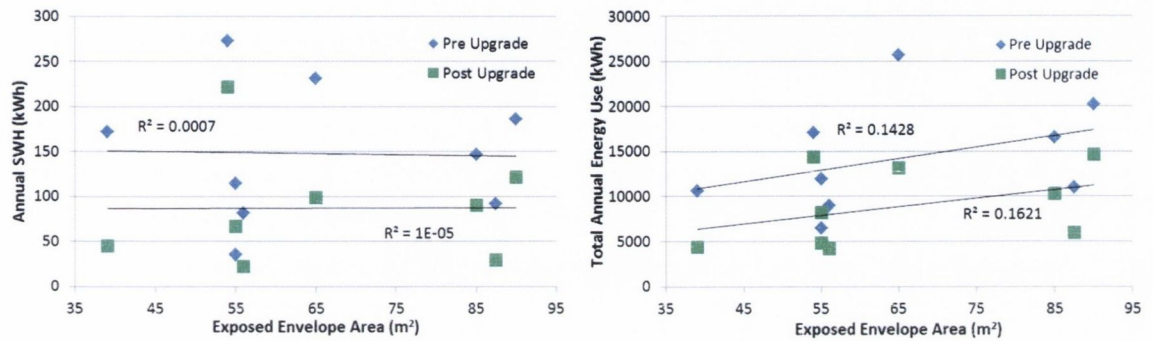


Figure 65 Annual SWH and Total Energy Consumption comparison with Exposed Envelope Area

With the exception of weekly income, with a very weak R^2 of 0.41, the analysis shows that there are no obvious correlations with any of the parameters. R^2 does not improve significantly when outliers are removed. The best correlation occurred when comparing the total energy consumption of the 2 storey dwellings with the floor area as shown in Figure 66. With pre- and post- upgrading p -values of 0.028 and 0.02 indicates strong evidence against the null hypothesis. It is common practice to characterise energy use in buildings by floor area.

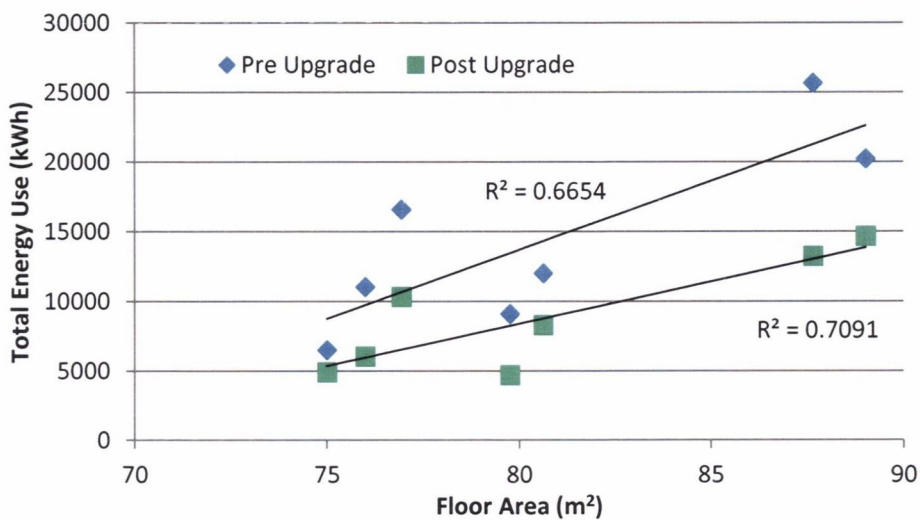


Figure 66 Total Annual Energy Consumption compared to Floor Area

In an attempt to find an expression to characterise the dwellings energy consumption in terms of floor area and income a multivariate linear analysis was carried out using the following expression:

$$E = \alpha + \beta_1 X_1 + \beta_2 X_2 \tag{Equation 11}$$

where:

- E is the energy consumption;
- α is the y-axis intercept;
- β_1 & β_2 are the regression model coefficients determined in the analysis
- X_1 is the independent variable area; and
- X_2 is the independent variable income.

The ‘linest’ function in Excel 2010 uses the least squares method to calculate a straight line that best fits the multivariate data and also produces uncertainty estimates for the fit values. The linest regression established the following term to express the relationship:

$$E = \alpha + 891(Area) + 7(Income) \tag{Equation 12}$$

Figure 67 presents the results of the linear regression analysis using Equation 12 to compare the measured total energy consumption and predicted consumption for the two storey dwellings.

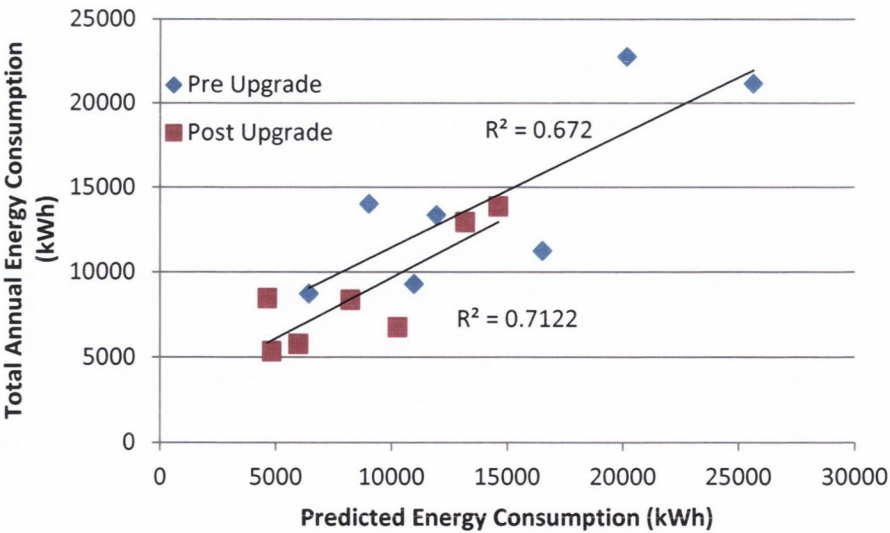


Figure 67 Pre- and post- upgrading measured versus predicted total energy consumption correlation with floor area and annual income

As expected R^2 is very similar to just characterising using floor area, where:

Pre- Upgrading $R^2 = 0.67$; and

t- stat is 1.84 i.e. < 2 therefore not statistically significant

Post- Upgrading $R^2 = 0.71$;

t- stat is 2.05 i.e. just about statistically significant

Previous research has shown that the convention is typically to relate domestic energy consumption to building floor area. This section demonstrates that this is not necessarily accurate. However, the sample is small and cannot be said to reflect the total population. Hence, this study maintains the convention.

6.8 Conclusion

This chapter presents the results of the multi-level quantitative analysis to assess the effect of energy efficient upgrading on energy use and evaluates the scale of the energy savings. Measured results were compared with theoretical delivered energy results from DEAP. This study found that the average measured energy consumption pre- and post- upgrading was 60% and 72% respectively of the theoretical energy predicted by DEAP for the nine dwellings. This is contrary to some previous empirical research, (Rogan and Gallachoir, 2011, Cayre *et al.*, 2011), which found energy demands to be higher than predicted. There was considerable variation in the result particularly following for the upgrading where dwellings G, H and F reduced their consumption considerably compared to that predicted. Care must be taken when drawing conclusions from these results. DEAP calculates performance independently of occupant behaviour and assume a standard heating year. Without further analysis it could simply be proposed that the measured data presented corresponded to warmer than a standard year. It may also be hypothesised that social housing tenants have less disposable income and may not be able to heat their homes to a comfortable level. The section highlights the trade-off between accuracy and simplified calculation procedure.

Initial observation of the monitored data demonstrates a wide variability of energy consumption patterns between the houses. There is also a difference between SHW and electricity consumption patterns. Observations supported by a linear regression analysis found that electrical consumption is independent of external climate or time of year. It is noted that consumption is stochastic in nature with peaks and troughs evident for no obviously apparent reason. It may be expected that electrical consumption would decrease during the summer period with less lighting, washing and drying and people tend to be more active during this time

of year. This was found not to be the case with no discernible difference in consumption throughout the year. This may be the case because the social housing occupants tend to spend a considerable amount of time in their homes. The majority of the occupants in the study were not working. This is further explored in Chapter 8.

The quantitative analysis demonstrates that actual energy savings were achieved as a result of the upgrading. The level of measured energy use and savings varied significantly between dwellings. The study found that there was a marginal decrease of 7.5% in electricity consumption and some of the dwellings actually increased their consumption. This is not surprising as the only improvement to the electrical system was the installation of energy efficient lighting. This is one of the few electrical dwelling constituents that DEAP calculates energy consumption and awards savings.

A statistical review of the measured data confirmed that there was a reasonable correlation between SWH consumption and HDD. However, as shown above this methodology is not suitable for short term, such as inter-day analysis. The analysis shows that it is particularly difficult to calculate a baseload for individual dwellings. The analysis established that comparing consumption for a 'normal year' in terms of external climate resulted in an average 47% reduction in SWH energy consumption. It is clear that there is a large variability in SWH consumption between dwellings that have very similar physical and occupant characteristics.

Dwellings C and G are almost identical³, and have similar occupant and income profiles. Pre- and post- upgrading combined SWH and electricity consumption for dwelling C is approximately 50% more than dwelling G. From the interviews and casual observations one of the reasons why dwelling G uses less energy may be because the head of the house says she fears the arrival of the bi-monthly bill. While in dwelling C the kids run the shower to warm the bathroom before getting in. Another contributor may be that the kids in dwelling G play sport on a regular basis and are rarely in the home. While the 21 year old in dwelling C is unemployed and spends most of his time indoors.

Comparing SWH and electricity consumption in isolation carries the risk that if one reduces the other may increase. Overall combined SWH and electricity energy savings for a 'normal year' reduced by 67 kWh/m²/yr. This represents an average annual kWh saving of 33%. In monetary terms this equates to a saving of approximately €410 per annum. This is obviously very welcome for the occupants who did not have to invest in the upgrading themselves. However, the payback

³ Dwelling C is Semi Detached and Dwelling G is Terraced

period is estimated on average to be approximately 24 years. This is a considerable payback period and for private homeowners this represents a long term investment.

The quantitative results revealed that there is not a correlation with buildings physical parameters and occupancy rate and occupant income. The variability in results for a relatively homogenous dwelling type demonstrates that occupant behaviour has a big input on consumption.

The variability of the results demonstrates that there is not a linear relationship between the level of technical energy efficient upgrading and energy use. If the households were less homogenous it could be expected that the income and occupancy would play a larger role. Therefore neither of these plays a big role as to why the energy is different. The results suggest that occupant behaviour and perception play a large role in energy use and that this behaviour is affected by cultural, habitual, psychological and economic inputs.

Heat loss from buildings occurs predominantly through fabric and ventilation/infiltration heat loss. The next section tries to estimate the proportion of infiltration heat loss occurs in each of the houses. Also during the interviews the occupants a number of occupant expressed their dissatisfaction with the newly installed ventilation system.

Chapter 7

7 Kilkenny Airtightness - Effectiveness of upgrading with respect to Airtightness

7.1 Introduction

Following on from the findings in the literature review and the results of the airtightness tests from the Waterford study, it is obvious that there is a paucity of real data relating to the airtightness characteristics and its effect on energy performance of existing Irish dwellings. Some studies, (Nabinger and Persily, 2011, Jokisalo *et al.*, 2009, Liddament and Orme, 1998), estimate the infiltration accounts for 10% - 50% of domestic space heating energy requirement. However, only nominal draught proofing is one of the eligible works under SHIP (see Appendix A). Hence it is evident that a more consideration needs to be given to airtightness upgrading policies.

This section evaluates the real effect of energy efficient upgrading on building airtightness and correlated energy performance. Technical findings from pre- and post- upgrading airtightness testing are presented and compared to DEAP modelled airtightness and compliance with Technical Guidance Document – Part L. An estimate of infiltration heating load is established for local climatic conditions. During the occupant interviews and through observations it became apparent that airtightness played an important role in the occupant's lives. In particular the occupants commented on the post- upgrading ventilation in the houses. Occupant perspectives of airtightness and ventilation upgrading are evaluated.

7.2 Test Procedure

As with the Waterford study testing was carried out on each house pre- and post- upgrading in accordance with the slightly updated ATTMA Technical Standard for dwellings (ATTMA, 2010) and Method B, of EN 13829:2001. During testing in-depth visual and smoke pencil tests were carried out. Air leakage paths identified by the smoke pencil test and simple observations were similar to those identified in previous research (Sinnott and Dyer, 2012, EST, 2005, Sherman and Chan, 2003, Jaggs and Scivyer, 2006b). Some notable observations included:

- in a number of houses the greatest single leakage path was through an internal vertical timber 'box-out' (approx. 175 x 175mm) encasing the waste and soil vent pipe which ran from ground floor level and penetrated directly into the unheated attic space (Figure 68 a).

- many of the existing passive wall vents had been partially or fully obstructed. In some cases the vents had been painted over a number of times or blocked by miscellaneous items and debris potentially leading to under-ventilation of rooms (Figure 68 b).

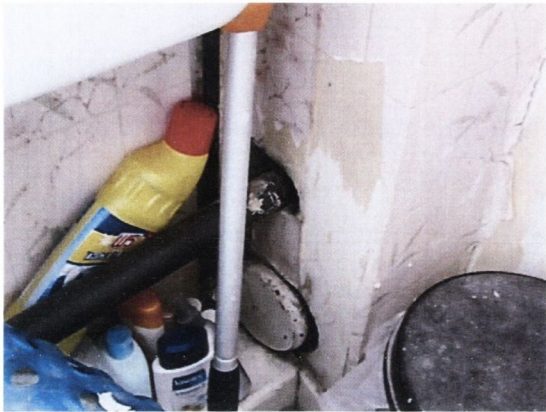
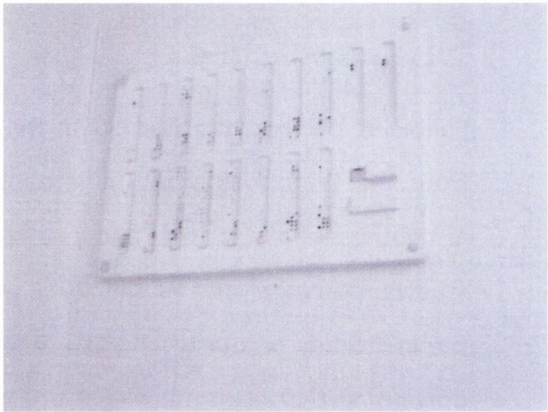


Figure 68 a) Soil Vent Pipe Box-out



b) Obstructed Wall Vent

7.3 Test Results

Figure 69 presents the results from the airtightness testing and DEAP assumed air permeability pre- and post- upgrading. Modelled airtightness is estimated using the DEAP calculated ‘structural airtightness’ multiplied by 20, to give an estimate of air permeability under test conditions, q_{50} , for each dwelling.

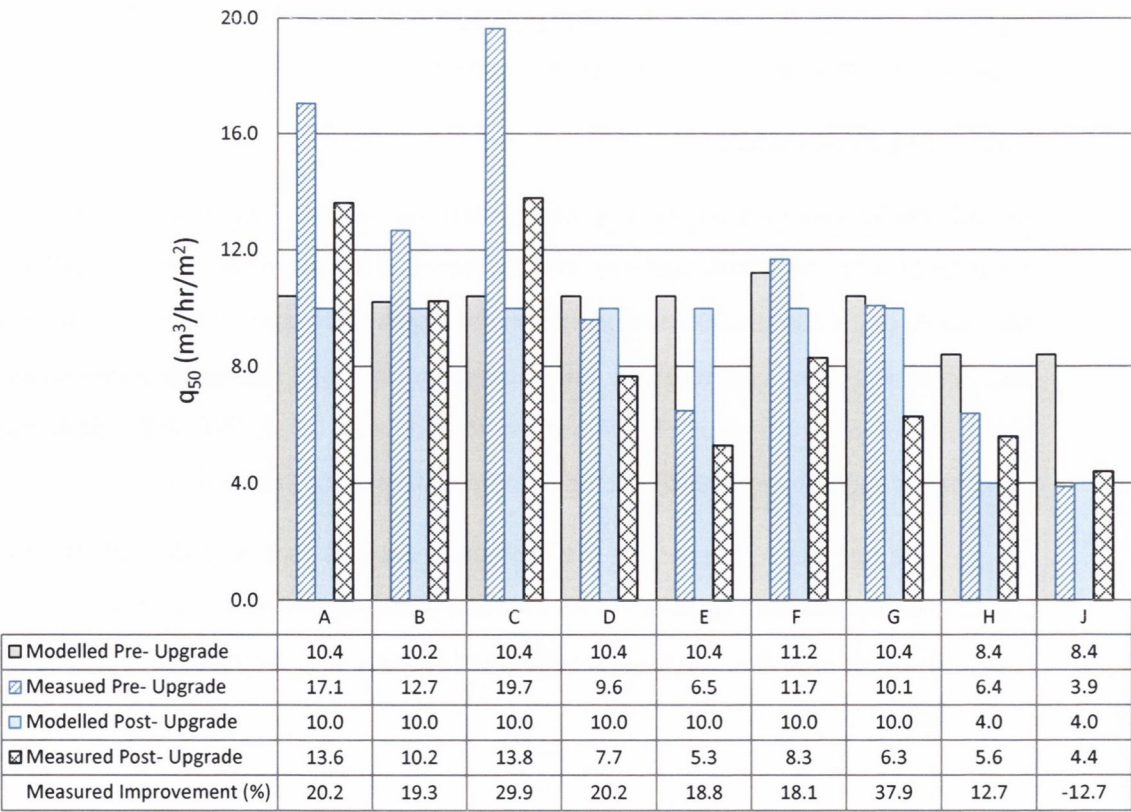


Figure 69 Calculated and measured airtightness pre- and post- upgrading

Pre- Upgrading

The DEAP calculated airtightness of the houses ranged from $8.4 \text{ m}^3/\text{hr}/\text{m}^2$, for both single storey houses, H and J, to $11.2 \text{ m}^3/\text{hr}/\text{m}^2$ for house F. The variation in predicted airtightness is based predominantly on number of storeys and percentage draught stripping. However, there was large range in measured air permeability from $3.9 - 19.7 \text{ m}^3/\text{hr}/\text{m}^2$. This represents an 89% difference between predicted and measured airtightness for dwelling C. This is consistent with the findings of a similar study by Sinnott and Dyer (2012). Overall, 44% of the results exceeded DEAP predicted airtightness levels, whilst 66% of the dwellings exceeded current Part L limit of $7 \text{ m}^3/\text{hr}/\text{m}^2$. Grouping the dwellings by number of storeys reveals that the two single storey houses not only performed better than predicted by DEAP, but achieved the highest levels of airtightness. The smoke pencil test reveals that is most likely because there is no leakage at first floor level where the joists penetrate the cavity and there is no soil vent pipe. There was some concern about under ventilation in dwelling J where the air permeability was less $3.9 \text{ m}^3/\text{hr}/\text{m}^2$. There was considerable condensation and occasional mould growth present during the survey. Typically when air permeability is less than $5 \text{ m}^3/\text{hr}/\text{m}^2$ mechanical ventilation becomes necessary.

Post- Upgrading

DEAP attributes only nominal energy savings by improving building airtightness when used to verify energy savings under the SHIP programme. Consequently, at design stage airtightness improvement works were not specified with the exception of nominal draught stripping. DEAP estimated an overall improvement of less than 4%, from 10.4 to $10 \text{ m}^3/\text{hr}/\text{m}^2$, by providing 100% draught stripping. However, testing revealed that upgrading increased airtightness from between 13 and 38%. Dwelling J was an exception. In this case, the open fire which had been permanently sealed by the occupants was replaced with a gas fire. With the flue closed during testing the measured air permeability increased by $0.5 \text{ m}^3/\text{hr}/\text{m}^2$. The overall results were positive; with the average airtightness levels increased 22%. Notably, post- upgrading, 66% of the dwellings were more airtight than the DEAP estimate with a mean air permeability of $7.7 \text{ m}^3/\text{hr}/\text{m}^2$. It is clear in this study using the 'structural airtightness' methodology that DEAP underestimates the positive effect of upgrading. The improvement is a function of all the upgrading works but it could be postulated that in addition to the draught stripping that the full-fill cavity wall insulation has the largest effect on air tightness as acts to seal the myriad of cracks and impede easy leakage from around floor joists into the cavity space.

7.4 Operational Infiltration and Infiltration Heat Loss

Climate induced infiltration of wind in low-rise buildings and stack effect, due to temperature differential, in high-rise are the driving forces of infiltration in most homes (Turner *et al.*, 2012). Heat loss from infiltration is not proportional to inside - outside temperature difference but subject to weather-dependent dynamic climate, and weather-independent envelope characteristics (Sherman, 1987). Wind induced pressure differential on the building envelope is highly dynamic and affected by a number of factors including:

- wind velocity, intensity and direction; and
- dwelling shape, height, topography, orientation, ventilation strategy and other physical structures.

Ireland's temperate oceanic climate and average annual temperature of about 9⁰ Celsius (C), summer mean maximum and winter mean daily minimum of about 19⁰ C and 2.5⁰ C respectively, means that dwellings are predominately naturally ventilated (MET Eireann, 2012). DEAP assumes a uniform climate throughout Ireland with an annual mean external temperature of 9.9⁰C and 7.6⁰C for heating season (SEAI, 2012b). However, this does not reflect the variability of the Irish climate based on geographical location when attempting to reflect real energy performance.

Operational Infiltration

There are high levels of uncertainty when trying to correlate pressurization data to operational infiltration, including, different measurement methods which result in comparison errors (Kronvall, 1980, Jones *et al.*, 2012). These factors alone make exact calculation of infiltration for a real building currently beyond the scope of accurate calculation. Thence, estimation techniques must be used.

The Lawrence Berkeley Laboratory (LBL) infiltration model developed in the early 1980's estimates infiltration by superposition of the contributions climate conditions and physical building parameters to predict the infiltration rate, Q. The model uses the blower door measurements in the form of Equivalent Leakage Area (ELA) to characterize the leakage of the envelope. Sherman (1987 p.p. 82) defines the ELA of a particular crack as "*equal to the area of a perfect nozzle (i.e., discharge coefficient of unity) which, at the reference pressure, would pass the same amount of air as the crack*".

Sherman and Grimsrud (1980) developed and presented expressions for stack and wind parameters for use in the model that reduced the need for a number of site-specific parameters. ASHRAE (2009) adapted these parameters and present simplified stack parameter, C_s , based in storey height and wind parameter, C_w , which utilizes a shelter class to calculate wind effect based on storey height. From this the infiltration rate can be calculated as follows:

$$Q = \frac{ELA}{1000} \sqrt{C_s \Delta t + C_w U^2} \quad \text{Equation 13}$$

where:

- Q is the infiltration volumetric air flow (m^3/s);
- ELA is the equivalent leakage area (cm^2);
- C_s is the infiltration stack parameter (Pa/K)ⁿ;
- C_w is the infiltration wind parameter ($\text{Pa}/(\text{m}/\text{s}^2)$)ⁿ;
- Δt is the indoor/outdoor temperature difference (K);
- U is the average local wind speed (m/s).

This model is widely used and adapted in simulation software. The ELA as a physical property of the dwelling leakiness is calculated at high pressure, typically 50Pa, whereas operational infiltration occurs at a pressure differential an order of magnitude lower, typically estimated at 4Pa, similar to DEAP. Therefore, to be useful ELA_{50} needs to be scaled to operating pressures.

Sherman (1987) adapted the LBL Infiltration Method and K-P estimation model to estimate infiltration under normal working conditions. The ELA can be reduced using the following:

$$ELA_4 = \sqrt{\frac{\rho}{2(4Pa)}} Q_{50} \left(\frac{4Pa}{50Pa} \right)^{0.65} \quad \text{Equation 14}$$

Air permeability can be normalized by building envelope area or volume. However, this normalization is only an estimate as air leakage does not scale with one dimension of the building. Consequently, Normalized Leakage (NL) has become a useful and popular metric whereby, leakage is normalized with respect to floor area (Area) and dwelling height (H), assuming the rule of thumb airflow exponent $n = 0.65$ (Chan *et al.*, 2013, Sherman and Dickerhoff, 1998, Chan *et al.*, 2012) as follows:

$$NL = 1000 \left(\frac{ELA_4}{Area} \right) \cdot \left(\frac{H}{2.5m} \right)^{0.3} \quad \text{Equation 15}$$

Here an NL of 0.55 corresponds to $ACH_{50} \approx 10$ (Chan *et al.*, 2013)

Infiltration Heat Loss

The heat load due to infiltration is commonly estimated using the classic linear expression, given as:

$$Q_{in} = \dot{m}C_p(t_i - t_o)$$

Equation 16

where:

- Q_{in} is the energy load (W);
- $\dot{m}$ is the mass flow rate (kg/s);
- C_p is specific heat capacity (J/kg °C) and;
- $t_i - t_o$ is the internal/external temperature differential (°C).

Therefore, in service energy consumption calculations are dependent on the infiltration mass flow rate under operational conditions. This study uses the blower door results and applies the adapted LBL infiltration model, Equation 13, to estimate the mass flow rate under in service conditions using the following input parameters:

Local Wind Speed

Table 10 presents the 30 year average monthly local wind data. The location of the dwellings has the lowest average annual wind speed in Ireland at 3.6m/s (MET, 2010).

Local Temperature

A portion of the heat loss through the building envelope is replaced by casual gains, occupant behaviour and passive solar gains. Also air absorbs heat as diffuse infiltration occurs through the envelope; unaccounted for this may lead to an overestimation of the energy impact (Younes *et al.*, 2012). Therefore, the energy balance is not simply the internal-external temperature difference. DEAP uses a utilization factor to balance these gains. This study utilizes Degree Days as an alternative method to balance incidental gains and mitigate the need to use utilization factors. An explanation of Degree Days is given in Section 2.14. Heating Degree Days (HDD) were gathered from a third party which monitors a weather station located approximately 2km from the case study dwellings. Table 10 presents the 6 year average, monthly and annual, wind speed and HDD_{15.5} data for Kilkenny (MET, 2010, BizEE, 2014).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean Wind Speed m/s	4.1	4.1	4.2	3.6	3.4	3.2	3.0	2.9	3.2	3.5	3.6	3.8	3.6
HDD @ 15.5°C	335	275.2	261.4	192	117	69.2	38.2	42.7	83.3	155.2	233.8	375	2178

Table 10 Monthly and Annual Wind Speed and Heating Degree Days; adapted from (MET, 2010, BizEE, 2014).

Wind and Stack Coefficients

Local factors established from ASHRAE Fundamentals (ASHRAE, 2009) Section 16.23, Table 4,5 and 6 where:

- Stack parameter for two storey house, $C_s = 0.00029$;
- Wind parameter, using building shelter class of 4, $C_w = 0.000042$.

The normalized leakage rate NL, calculated using Equation 15, and summative predicted energy requirement and energy savings pre- and post- upgrading for each dwelling is presented in Table 11.

Dwelling	Pre Upgrading			Post Upgrading			Saving kWh
	ELA ₄ cm ²	NL	kWh p.a.	ELA ₄ cm ²	NL	kWh p.a.	
A	717.7	2.2	2386	572.9	1.7	1905	481
B	637.5	1.9	2120	514.6	1.6	1711	409
C	807.8	2.5	2686	566.7	1.7	1884	802
D	469.3	1.4	1560	375.0	1.1	1247	313
E	267.2	0.8	888	214.6	0.7	713	175
F	416.7	1.3	1385	258.3	0.8	859	526
G	391.7	1.2	1302	321.2	1.0	1068	234
H	147.1	0.3	489	128.1	0.3	426	63
J	137.4	0.3	457	154.8	0.3	515	-58

Table 11 Pre- and Post- Upgrading Normalised Leakage and Energy Use

The total infiltration heat loss for the nine dwellings pre- and post- upgrade is estimated to be 13275kWh p.a. and 10328 kWh p.a. respectively. This equates to an average 327kWh or 22.2% annual infiltration heat load saving. The mean NL for the dwellings pre- and post- upgrading is 1.3 and 0.8 respectively. The normalised SWH annual consumption figures were used to estimate the proportional infiltration heat loss for each of the dwellings, pre- and post- upgrading, as shown in Table 12 and Table 13. The average proportional infiltration heat loss pre- and post- upgrading is 14 and 20% respectively. These results may be taken as conservative. Removing the water heating portion of the SWH figures would increase the proportional infiltration heat loss.

Dwelling	A	B	C	D	E	F	G	H	J
Measured SWH (kWh/yr)	9231	16576	11272	20274	2965	7425	6477	7967	13594
Infiltration Heat Loss (kWh/yr)	2386	2120	2686	1560	888	1385	1302	489	457
Pre - Upgrade infiltraion (%)	26	13	24	8	30	19	20	6	3

Table 12 Proportional infiltration heat loss pre- upgrading

Dwelling	A	B	C	D	E	F	G	H	J
Measured SWH (kWh/yr)	5370	10857	6934	8641		2405	1820	2099	11031
Infiltration Heat Loss (kWh/yr)	1905	1711	1884	1247		859	1068	426	515
Post - Upgrade Infilltraion(%)	35	16	27	14		36	59	20	5

Table 13 Proportional infiltration heat loss post- upgrading

It is clear from the results that there is a significant increase in the proportional heat loss as a result of infiltration post- upgrading.

7.5 Occupant Perspectives

This section presents the outcome of the occupant interviews and researcher observations in relation to dwelling airtightness pre- and post- upgrading.

Pre- upgrading

Generally the occupants considered their standard of living to range from '*fairly good*' to '*very good*'. While a number remarked that their homes were draughty there was a general uncertainty in 8 out of 9 householders about the significance of adequate ventilation, the denotation of infiltration and its influence on building energy load. Over the winter period, three households placed curtains or blankets at the front and rear doors and the occupants of dwelling C placed towels around the kitchen units to act as draught excluders. A visual inspection revealed large unsealed penetrations into the service duct 'box out' which was previously highlighted as a common leakage pathway. The box out was identified as a particular problem in a number of dwellings both in the kitchen and directly above in the bathroom. Dwelling D reported the ingress of water and air around the windows depending on wind directing and intensity. This was attributed to poor installation of the windows rather than the window quality.

The positioning of passive wall vents was identified as problematic in a number of dwellings. Where beds and seating were positioned below the vent, occupants expressed that there was discomfort. Most occupants sealed the vents using tape or arbitrary materials. It is worthy of note that in dwelling C, which had the overall worst pre- upgrading test result, the adult female occupant always sleeps with the window slightly open, regardless of season. The post interview survey of the bedroom revealed that there was no passive wall vent and the window trickle vent was permanently closed. This indicates an under ventilation problem in the room.

A real exception in the study was dwelling J, which had the highest levels of airtightness. The occupants expressed that as a result of the female occupant's chronic illness, meaning she constantly feels cold, all accessible air infiltration pathways and design ventilation were sealed '*to retain as much heat as possible*'. The male occupant is aware of the condensation and mould growth and believes that the dwelling environment contributes to his wife's illness, but believes they have no option as they need to maintain a high temperature. Generally occupants have done little or no remedial work to prevent heat loss through infiltration citing: either that they are not capable of carrying out the works or that they do not have the money to hire a professional and ultimately the onus is on the Local Authority.

Post- upgrading

Feedback from the occupants was broadly positive and they felt that their homes were warmer and easier to heat. Each occupant expressed real satisfaction on two levels where external doors and windows were replaced:

- Reduction in draughts; and
- To a greater extent by improving the aesthetic quality of the house.

However, the installation or reinstatement of passive and active design ventilation was raised as a problem in six dwellings. The female occupant of house A described the overall upgrading as positive but says her bedroom is *'freezing'* due to installing the new wall vents in each room. Prior to upgrading the window trickle vents were always closed *'to keep the heat in'*. The occupant also says she *'can't enjoy the television because of the noise'* from the breeze moving through the vents. The female adult in house C now hears more noise coming from the street *'which is very annoying'*. She also believes that the vents have caused cross *'draughts'* between rooms and believes the house is too small for so many vents. Following the second interview she now plans to block up at least some of the vents. However, she still *'has the habit'* of opening her bedroom window at night. This conflicts with the increased noise agreement but she says that the noise levels at night are several times lower than during the day. Dwelling D occupants expressed dissatisfaction with the newly installed passive wall vent in the sitting room saying *'it was freezing sitting under the one in the sitting room..... now it is sealed with tape'*.

The mechanical vents installed in each bathroom received almost unanimous negative comments. Almost all felt that they did not work effectively. Dwelling D occupants turned the fan off at the master switch and sealed it with tape because *'it was too noisy when having a bath'*. Occupants particularly dislike the fan activating every time the light is turned on. This is a particular problem at night because the noise of the fan disturbs other sleeping people. Almost all occupants expressed a preference to open the window and purge the room with fresh air when required; in essence a simple form of demand control ventilation (DCV) system. In House J, both gas fire and gas boiler are located in the sitting room. The occupants didn't understand the importance of having high and low level design passive ventilation. Post interview, they intended to block up the low level vents to limit *'draughts across people's feet'*. This is an obvious health and safety risk.

Reflecting on the occupant's perception the majority are ambivalent about the importance of adequate ventilation and impact of infiltration on energy use in their homes. Overwhelmingly their priority is to run the house with minimal expense. Consequently, they are keen to maintain heat within their homes, even if it means compromising airflow by blocking up vents or leaving window trickle vents closed.

7.6 Conclusion

This chapter provides an insight into the difficulty of accurately predicting infiltration in naturally ventilated buildings. Superficially each dwelling, by type, was identical but standard blower door testing revealed a large variability in envelope airtightness. Operational pressure on the envelope is highly dynamic. True leakage path characteristics are seldom known and are very challenging to measure under working conditions. Consequently, there is a balance between choosing complex models with improved outcome accuracy and simplified models which allow ease and speed of calculation. When using a simplified model attention must be given to accuracy of the model when assessing a single building or building type.

The study showed that the DEAP 'structural airtightness' methodology does not apply adequate energy savings by improving airtightness. Hence, upgrading strategies largely ignore the potential of envelope tightening. Interestingly blower door testing revealed a significant improvement in envelope airtightness as an unintentional co-benefit of standard upgrading. When these airtightness tests results were included in the DEAP calculation the final predicted energy saving was much greater than reported. To increase the potential for energy savings credits, airtightness tests should be carried out on all dwellings pre- and post- upgrading.

The results from the simplistic weather-dependent model demonstrated that air infiltration plays a large role in the energy performance of dwellings. Using the measured performance of the dwelling for a 'normal year' the average proportional infiltration heat loss pre- and post-upgrading equates to approximately 14% and 20%, respectively, of the dwellings heat load. The study applied a large number of assumptions to the predictive modelling and there is inherent uncertainty in the results. It would be expected that there would be some level of 'take back' as a result of the upgrading and all potential saving may not be realized in practice. Achieving high levels of airtightness is challenging in existing dwelling but tangible reductions in energy consumption can be achieved by actively improving airtightness, often through inexpensive interventions.

There is a great awareness that occupant behaviour has a large effect on building energy consumption, but there is a lack of understanding of how people interact with and perceive their environment. Ventilation and infiltration was not a major concern for the occupants. In principle, the installation of design ventilation has a simple outcome. In practice this was not the case and a number of people intended to block up vents that were installed as part of the upgrading. In the case of house J there are real health and safety concerns about blocking the sitting room vents.

Further research is required to improved accuracy of simple predictive airtightness and energy models for Irish dwellings. The first step along this path is to undertake and formally collated wide scale airtightness testing. Airtightness testing should be encouraged for all envelope adaptations to dwellings to maximize energy savings credits.

Designers need to explore the relationship people have with their homes and understand their perceptions of dwelling adaption on their quality of life. Overall the occupants seem happier with their new front door from an aesthetic viewpoint rather than impact on energy use and comfort. To maximize the benefits of upgrading it is clear that there should be multiple liaison sessions with occupants before, during and after works to ensure they understand why a particular process was carried out, whether regulatory or voluntary, and how to correctly deal with any new systems or processes.

Chapter 8

8 Interviews - Effectiveness of Upgrading with Respect of Occupant Perspectives

As stated earlier, an integral aim of this work was to research with the occupants rather than just about them. The researcher was keen to explore the occupants' lifestyle patterns and attitudes and how this impacted on their energy use. To help gain this knowledge, each occupant was formally interviewed at least twice. There were also several brief encounters and casual conversations over the almost year research period. This allowed for a strong rapport to be developed with the occupants and gave them time to express their views. Because the research allowed for a detailed profile to be built up on each house, the findings are presented initially as detailed individual case studies. This is followed with an analysis of the general regularities and patterns that were found in the data. This element of the study is not aimed at gaining a complete understanding of human behaviour in the home. Instead the aim is to incorporate the variable of human behaviour into the examination. All occupants were given a pseudonym.

8.1 Dwelling A

8.1.1 Pre- upgrading Interview

Jane, 49, lives alone in the mid-terrace house and has lived in social housing all her life. Her daughter has two children and resides close by. Jane worked most of her adult life in childcare but hasn't been employed since 2009. Jane's medical issues prevent her from working and limit her mobility. She is *'constantly in the house'* and usually only leaves the house to drive her daughter back to her house and would be gone for a maximum of 3 hours. Jane's sister typically runs her errands *'I'm pure lazy, but I get fed up looking at the same four walls'*. Jane watches TV most of the day and uses the iPad at the same time. She uses her iPad for Facebook mostly. *'People don't come out as much in the winter'* and not too many people call to the house. When asked about energy use, she stated *'when I was young and even still I never thought of energy, even still everything is plugged in and turned on'*. The only thing that is fully turned off at night is her TV because the socket is easy to access. *'I'd go off and leave the TV on; I could be gone two or three hours.... it's just laziness, the hassle of fiddling with all the controls'*.

Standard of living

Jane feels that she has a good standard of living because the house is warm since she got gas central heating. It actually gets so warm that she can't have the heating on when cooking in the kitchen. In fact, the small kitchen window is left open all the time unless it's a very cold night.

Jane predicts that post upgrading *'I'll be tellin ya it's too warm'*. *'Since I got in the central heating in 5 years ago it's a warm house, but it was freezing before that'* when she had the solid fuel stove in the kitchen. The main reason for her changing from solid fuel heating to gas was her inability to carry a coal bucket. The house is just the right size for her on her own and she likes the location very much. She says the *'sun is in the kitchen in the morning and sitting room in the evening'*. This is a surprising comment as the house is orientated the other way around.

Bills

Jane uses bill pay for both her gas and electricity and manages the bills by paying €20 - €25 per week to each through the post office. *'I could have €400 on the gas after paying the bill'*. This balance is usually more than that on the electricity. The balance builds during the summer, but sometimes when the bill comes there may be an outstanding balance. She terms her budgeting as *'trying to cover my back'* mainly because prices are rising all the time and the day might come when she does not have the money to pay. Jane does not examine her bills saying *'so long as I'm in credit that's fine'*. However, sometimes she wonders how her electricity bill is so high. She will never change service provider from Electric Ireland simply because *'I hate change'*. When asked: How energy conscious was she, she replies – *'I am not at all energy conscious'*.

Heating and hot water

The house has gas central heating and an open fire in the sitting room. The central heating is turned on and off as required and the on/off timer is rarely used. The open fire in the sitting room is only used at Christmas mainly due to Jane's inability to carry the fuel. If there was someone available to carry the coal she would light it more often saying *'it would save energy because I am on my own I only need to heat this room (the sitting room) and the rest of the house doesn't really matter'* and unlike with gas *'at least with the coal you would have it paid for'*. Generally the hot water is from the heating system but sometimes she would use the kettle for *'a sink full of water or the mop bucket'*. The kettle is always used during the summer because the immersion has not worked in a number of years. When asked where she thought the heat from inside the building goes: she said *'up the chimney, and probably out through windows and doors when left open'*.

Appliances

Cooking

Jane has an integrated gas cooker and hob but uses it only a few times during the week. She has a small electric oven that she uses twice a day – *'I'm always using it, cause it's on counter and it's*

handier'. She also has a second electric oven with a grill function and uses it *'cause it's quicker than the oven'*. She goes on to explain that because she uses the electric cooker the gas bill isn't high. Though there is a microwave and toaster in the house they are rarely used. She always boils a full kettle of water even for a single cup of tea even though Jane is on her own most of the time. The left over boiled water is then replaced with fresh water each time. Jane says *'I know the metre goes around like 90 when the kettle is on'*.

Televisions/Phones

There are two televisions in the house, one large TV in the sitting room and a 21" in the kitchen. Jane watches the one in the kitchen in the morning but moves into the sitting room from lunchtime and watches it until bedtime...a total of 8-10 hours. While in the sitting room watching TV Jane would also be on her laptop for up to 5 hours per day and it is left plugged in all the time. The TV in the kitchen would usually be left on all day even if there was no one watching it. Jane says she would also leave both televisions on regularly and would leave the house to *'run errands and I'd come back after dark and all you can see is the sitting room TV flickering'*. She seems to leave appliances on out of habit. She has two phones because her friends are in different free networks. She has wireless broadband. The stereo in the kitchen is left turned on 24/7 and turned up and down as required.

Washing & Ironing

The washing machine is used up to three times a week. She would wash her clothes even if the load wasn't full if Jane's grandchildren are visiting but tries to wait for a full load and uses the dryer depending on the weather. This averages twice a week to dry towels. She irons once or twice a week, vacuums about twice per month and used the dishwasher a maximum of once per week.

Buying appliances

Good brands are important to Jane. When purchasing white goods she believes you get what you pay for. Her previous washing machine was a Zanussi which lasted twelve years and so was willing to pay €500 for her current four year old Zanussi machine. However, *'sometimes you have to go with the cheaper brands, cause you can't afford it..... my dryer is a cheap one'*.

Shower

'The electric shower is constantly going', for up to half hour per day, *'I turn it on and close the door cause it makes the bathroom nice and hot'* and continues to say *'I don't need to leave the radiator on in the bathroom'*.

Lights

There are only four bulbs in the house. For some reason, Jane does not like light bulbs over her head and does not turn them on unless completely necessary. When asked did she think that low energy light bulbs saved money she replied: *'I don't know that, they're supposed to. They're not going to be sold if they don't'*. She was asked: What do you believe the cost of an energy saving bulb is? She was of the view that they would cost 7–8 euro and interestingly thought that *'they don't last as long as an ordinary bulb'*.

Defining Quote: *'After that talk, I'll have to start turning things off'*

8.1.2 Post- upgrading Interview

Since the upgrading Jane's health has gotten worse. She says *'maybe if I got up and moved around a bit I wouldn't be as cold'*. *'I do a three mile walk every day in my head but my legs don't move'*.

Standard of living

Jane describes the house as *'freezing'* ever since the upgrading. She believes this is primarily due to her health but also the installation of the passive wall vents in each room. Before the upgrading there were trickle vents in the windows but they were always kept closed *'to keep the heat in'*. Jane says *'with the vents you can't enjoy the tele because of the noise'* of the breeze moving through the vents. However, Jane states that her partner and sister say that the house is warm. The neighbours say the house is like a furnace. Overall she describes the upgrading as positive *'the only thing I can't stand are the air vents, the noise drives me bananas'*. There is a vent in every room and an extractor fan in the bathroom which comes on every time the light switch is turned on. Even when it's turned off the wind from outside makes it turn.

Heating and hot water

The heating system was one single zone and a manual clock on/off control prior to the upgrading. There is now a three zone heating system with a seven days programmer. This causes problems as Jane forgets to set the required heating and though the heating is on downstairs it may be cold upstairs or there is no hot water *'before everything was together and now it gets tedious having to change it all the time'*. Although she was shown how to use the seven day programmer she still says she can't use it *'he may as well have been explaining to the table, sometimes it take a long time for me to take things in'*. When the heating was installed in August it was set to come on at seven am and Jane couldn't figure out how to reset it so just turned it off. *'I use it manually and I'm constantly out in the kitchen pressing buttons'*. The open fire was replaced with a stove but

she still doesn't light the fire because she *'has to drag coal'*. She still finds herself boiling the kettle on a regular basis.

Bills

She still pays €20 - €25 per week for her utilities.

Appliances

Appliance usage is in general the same, televisions and other appliances are still left turned on. The only thing is that her partner turns off the lights. Jane replaced her laptop with an iPad at Christmas 'I stay in the bed and could be on my iPad until my eyes start closing, and could wake up at five or six in the morning and be on it again'. Though she spends a lot of time on the internet she finds technology difficult to master particularly such as booking flights.

When asked - Do you still turn on the shower to warm the room? she replied: *'Sometimes, I won't be doing it too much longer..... when the water rates come out'*.

Defining Quote *'I miss the hot water with new system'*.

8.2 Dwelling B

8.2.1 Pre- upgrading Interview

Dwelling B is a well maintained and decorated three bed end of terrace house with a compact kitchen in the rear extension. The exposed gable of the house is north facing with the front of the house facing West. The ground floor is open plan with the original kitchen converted to a living room and the original sitting room is a dining room. Sam and May are in their late fifties and have a large family.

Sam's work routine varies greatly and he often works irregular shifts with a mixture of days and nights and he usually spends between 12 and 14 hours in the house. May is a smoker and spends on average 23 hours a day in the house where she currently cares for two of her grandchildren saying *'there is always activity in the house'*. She says *'I never leave the house.....Sam even does the shopping'*.

They believe they are *'reasonably energy conscious'*.

Standard of living

Sam believes that their overall standard of living is *'fairly good'* but May disagrees and thinks that it is poor, saying *'this is the worse house I was ever in in my life'*. May describes the house as

being *'like a freezer in the winter'*. In reply Sam says: *'you see that's where we differ a bit... I hate too much heat so I think with the exception of the kitchen it's ok.... but that's the way I am anyway'*.

Sam states that *'the standard of construction is poor'*. For example, the internal soil vent pipe in the corner of the sitting room is not sealed to the attic space and there is a draught and the roof leaks and allows water ingress. Sam also installed double glazed windows, spending his own redundancy money from a previous factory job. Both are happy with the size of the house and like the orientation. However, May states *'there is definitely something wrong with the house'*. The front door of the house is leaking around the frame and sometimes black appears around the bedroom windows. Sam thinks it is just condensation but May believes that it isn't condensation and that the windows are leaking. On further investigation, it seems that the windows and doors were poorly fitted.

They describe the box room as cold – external walls on north side and used to be over the porch. The kitchen extension is described as being very cold and because of the open plan design they use a curtain to separate the kitchen and dining room.

Heating and hot water

Space and water heating is provided by the gas central heating system. There were two fireplaces as with typical social houses of this era. But now there is just a gas fire in the sitting room. The fireplace in the original sitting room was blocked up predominantly because smoke came through from the neighbours. Secondary heating is from a gas fire mounted in the fireplace. There are problems with the gas fire because they believe it was not fitted correctly and there can be a backdraught. *'The fire would be on every evening'* because there is no radiator in the sitting room. May says *'you would freeze to death'*. Both like to control the heating. Sam says *'there is often a row because I come in and I'm sweating and May would be freezing'*. The gas is always used to heat the water because the heating is always on. The water was heated by immersion before they had the gas installed but has not been used for seven years because *'it's too expensive'*. We could always heat the water and radiators separately.

Utility Bills

Sam replaced the standard gas meter with a prepay meter which was offered free as part of a scheme. He tops up the card every week when he does the shopping and budgets the lodgement based on the weather. He also lodges between €20 and €30 into his electricity account. May says

she would like to replace the electricity meter with a prepay meter but presently there is a charge. Sam does not examine the electricity bills and pays any balance in the post office.

Appliances

Cooking

The electric cooker is used in the morning and then again in the evening to cook dinner, usually for not more than an hour. The microwave is used *for '15 – 30 minutes per day and sometimes even more'*. *'We all (including the children not living there) come in at different times and the dinner is done so we heat it up'*. *'The kettle is on all the time'* and is boiled 10 – 11 times per day for tea and making food for the children. The toaster is not used every day. They have a fridge and a fridge freezer. There are two mobile phones.

Televisions/Phones

There are three televisions in the house. The small TV in the bedroom is never used and there are two 39" TVs in the sitting and dining room (approx. 8 feet apart). The sitting room TV is on most of the day on the saorview kids channel and watched from 7pm – 11pm in the evening. The dining room TV is only used to watch sport. All televisions are turned off completely at night. But *'when Jamie is here there are red lights all over the place'*. The DVD is only used the odd time. There is no computer or laptop in the house thus, no broadband, except when Jamie comes home. The TV is left on when May would be cooking *'I mightn't be looking at it but I'd be listening to it'* and the radio is always on in the kitchen.

Washing & Ironing

'The washing machine is used most days' and the cycle is about one hour. The tumble dryer is used sporadically depending on the weather. Sam says *'she irons everything'* and May says she irons *'at least 6 hours per week'*. The dishwasher is used every day and vacuum cleaner is used most days.

Shower

The power shower is used about 15 minutes per day.

Buying appliances

When buying white goods the make is the most important *'but recently in the last few things that we bought I (Sam) would look at the rating'*. May looks at the size of her washing machine *'look at the cost of cleaning curtains or duvet in a cleaners, that's why I go for a big washing machine'*. Sam *'you get what you pay for'*.

Lights

Both Sam and May believe that energy saving bulbs save money and last longer. Consequently, Sam replaced a number of the existing bulbs with energy saving bulbs about a year ago. The bathroom light is left on all night because May does not like the darkness and likes a 'small light'.

Asked: Can you name the different light bulb types – May says *'I haven't got a clue'*.

8.2.2 Post- upgrading Interview

Sam believes that overall the *'house is better'* and he feels a difference in that the house heats more quickly and retained the heat longer. May says she still finds the house very cold and that *'not everything is perfect'*. Sam says *'that's because May is a cold person and I'm a warm person'*. During the interview, May was asked if she was cold now to which she replied *'yes, freezing'*. The recorded temperature in the room was 19°C. It is noted that May is wearing light clothes, whilst Sam is wearing a shirt and jumper.

The newly installed windows and doors mean that there is no water getting in around the front door and the black mould has disappeared from around the windows. The gas fire in the sitting room was refitted but is never used. Sam says there is soot coming down the chimney and thinks there is a problem with the flue. May says *'the kitchen is warmer'* because the passive vent over the kitchen counter is repositioned to a different location in the room. She also says that upstairs is warmer than downstairs and it stays warmer at night.

Heating and hot water

Sam says he puts on the hot water for one hour in the morning and that this would last most of the day. They use the zoning controls which they find easy to work. However, they don't use the timer. Instead they opt to use the one hour boost option and May also uses the gas fire throughout the day. Sam says *'when you do turn it on it heats up pretty quickly'*. However they do not really notice any difference in the overall cost of heating before and after upgrading. Sam checks the meter and buys what he thinks he will need for the week when going to the local shop. This usually works out at €20 - €40 euro per week. They are happy with the overall cost of their gas and compare it to the cost of oil for some of their children. Again, they say they would like to have a prepay electricity meter. Sam has checked the fire versus the heating and says that the fire is more expensive than the heating for an hour.

Vents

The low vent in the sitting is still causing a draught behind the couch at lower levels. However, an improvement was that the existing vent in the kitchen above the sink was moved to another external wall and the draught is gone. The louvered vent above the couch was changed from pointing down to up as part of the upgrading which they say makes it much more comfortable to sit under. May does understand that it is important to have vents because of the risk of carbon monoxide. Also nothing was done with the SVP in the corner of the sitting room and there is still substantial air and some water ingress to the room. The vent in the bathroom was initially working until the external grill was replaced and some expanding foam was inadvertently deposited around the fan preventing it from working and partially blocking the vent pipe. Consequently *'there is a constant breeze through and noise from the vent'*.

Overall they do not feel anymore energy conscious and their son still always leaves the TV on. However, they are careful only to stack belongings on the decked section of the attic avoiding the new insulation.

Upgrading took less than 4 weeks to complete but May says that there is still work to be done and the workmanship was poor.

Defining quote: Sam speaking about the upgrading says *'if I was paying for it, that would be another thing..... whether you would get value out of it, I don't know'*.

8.3 Dwelling C

8.3.1 Pre- upgrading Interview

Amy, (mid 40's) and her two children John (early 20's) and Aaron (teenager) live in a three bedroom semi-detached house. The house is orientated on a North East to South West axis with a northerly exposed gable. They have lived in this house for seven years. Amy has worked two days for a number of years. Her income is augmented with lone parent's payment from social welfare. The house is clean and decorated to a good standard. John is unemployed and spends most of his time in the house and Aaron attends secondary school. The house is occupied for an average of 22 hours per day.

Standard of living

Amy believes her family have a good to very good standard of living. The house is of adequate size for the family but she feels that the box room is a little small for Aaron. Amy likes the location of the house because it is close to the supermarket and more importantly to her

mother's house, which she visits every day. She believes that the house at present is warm which *'is something to do with it being semi-detached'*. She likes natural sunlight and one thing she doesn't like about her house is that there is rarely sunlight in the kitchen. Consequently, she does like spending time in the sitting room to get some sun. There is a draught in the hall in the winter which she blames on the attic, but has not done anything to remedy it. She considers herself to be *'fairly energy conscious'*.

Bills

Amy does her household budget through the post office where she sets aside €15 per week for gas *'that has me well covered on my gas bill'*. She says the electricity bill is *'too high for a small house'*. She examines her electricity bills and has gone through it with her kids and blames it on the shower being on all the time and *'the TV's are on half the night'*.

Heating and hot water

The house has gas central heating and a solid fuel fireplace in the sitting room. The central heating is just turned on when the house gets cold. *'I wouldn't be one for having the heating on before I get out of bed in the morning'..... 'I just put it on as I need it'*. Amy lights the sitting room fire every evening during the winter and burns coal, timber, peat briquettes and turf, spending approximately €20 per week and €30 in a cold week on fuel. She uses the immersion every day for hot water for washing up etc... because *'it's the quickest'*.

Appliances

Cooking

Cooking is usually done on an electric cooker. She says that this is only used to cook the dinner in the evening but it could be on for 1.5 hours because the kids cook at different times. She does not use the microwave very often either but uses the toaster almost every day. She boils the kettle at least 5 times per day but just measures in *'two cups or whatever's needed'*.

Televisions/Phones

There are four televisions in the house. David has a 40" and Aaron a 32" and Amy a 14" in their own bedrooms. The 39" TV in the sitting room is on for approximately 10 hours per day where they have their skybox with a basic sports package. At night, the TV is turned off but left plugged in because the kids would be recording programmes. The radio is usually left on in the kitchen during the day even if no one is in the room. However, when going away Amy switches everything off completely because *'I was told that on standby it would still be using electricity'*.

The house has wireless broadband and a single laptop is shared amongst everyone and is used for at least 8 hours per day, mostly for Facebook. There is a DVD player in the house but this is rarely used because they watch films on the laptop.

Washing & Ironing

The washing machine is used almost every day but Amy uses the tumble dryer very seldom.

Buying appliances

The biggest driver she takes into account when choosing an appliance is cost. Amy explains that she would like to buy 'A' rated appliances but they are usually more expensive.

Shower

Amy heard that her electric shower was *'the worst thing for raising the electricity bill'*. She has told the kids to cut back because *'what I find is that they run it to warm the bathroom, then jump in, rather than turn on the heating, which adds up to about a ½ hour each. I would be just in, wash myself, and out again in 10 minutes'*.

Lights

The house has no energy efficient lighting. The kitchen has six recessed halogen bulbs in the kitchen and another two in the hall. The sitting room has five 40W bulbs in a rose. Lights are regularly left on around the house particularly by her children. When they move from room to room they don't tend to turn off lights. If her youngest son is going to the bathroom *'he will turn on hall, landing and bathroom light on the way up but often will not turn them off again'*.

Amy does believe that low energy lights do save money but she doesn't use them because *'you see ones for 80c and you see a couple of euro for the other ones and you go for the cheaper option' 'I just go with the cheap'*. She does make the point that she knows she is probably losing out in the long run.

8.3.2 Post- upgrading Interview

Overall, Amy is very happy with the upgrading but says *'the only thing that drives me bonkers are the vents'*. Amy installed a prepay electricity meter in late February 2013. She is unsure of exactly how much it costs. She estimates about 30 cents per day for the service and finds it a good system because she can keep track of what she is spending. An unintended co-benefit is that the whole family have become more energy conscious since the introduction of the pre-pay. Her sister and other friend have said that they are also going to get it installed. The meter has a digital reading showing the remaining credit balance. She says: *'I'd never go back..... it just makes you*

so aware of what I was wasting'. She says that she can now check how much it is to boil the kettle or wash clothes 'but I haven't gotten around to it yet'. The lads never noticed the electricity bill when Amy paid it in the post office but when they see her having to top up it has made them more aware. She is very happy with the wall insulation because it has stopped the draught coming through her kitchen units. 'It was so bad I used to use towels to seal around the presses'. She believes 'the house is holding the heat for a lot longer'.

Amy expressed some dissatisfaction with the duration of the upgrading, explaining that workmen would do two days' work and not return for another three days. She says *'it's hard 'cause you are living in the house and you can't live in dirt and it's hard to have your dinner in the middle of rubble'.*

Heating and hot water

Post- upgrading, the children still spend at least half an hour in the shower and often turn on the shower to heat up the room. However, post installing the prepay meter they have considerably reduced their time in the shower. Amy finds the zoned heating to be very good *'if I want hot water I just put it on for a while'* and says she has only used the immersion once since it was installed, whereas previously she used it every day. She also finds the upstairs/downstairs zoning very good. Previously she would *'be turn on and off radiators the whole time'*. However, she says *'I can't figure out the programmer'* and only uses the one hour boost button when she requires the heating saying *'I don't like heating on in the morning'. 'I turn it on and off as I need'. 'I put on the gas for the hot water'*. She uses the gas to heat the water rather than the immersion because she is always in credit on the gas.

At first Amy didn't like the idea of a stove *'because I love the open fire'* but now says *'they are a brilliant stove and I love it'*. She doesn't light it every evening in the winter because the kids get too hot and have to open the window. She now only burns some peat briquettes and timber that she received as a Christmas present from her mother. I have a lot of fuel and she says a bale of briquettes now lasts more than a week. When she noticed the bills reducing it spurred her on to do more. Pre- upgrading and pre- pay meter she would turn on the tumble dryer and say *'sure it will be on the bill, what difference'* and forget about it.

Appliances

It is clear that though no effort was made to influence energy use the pre-upgrading interview had an effect on the occupant's energy use behaviour.

Cooking

Cooker is used every day for an hour or 1.5 hours. She says after taking part in the initial interview *'it opened my eyes a bit'.... 'I turn things off now'*. However, all during the interview that TV was on in the room and turned own.

Televisions/Phones

One of the TVs has now been sold because her son needed to fund the purchase of a motorbike. There are still three TVs in the house. The laptop is now always plugged out at night.

Washing & Ironing

She says she has changed her behaviour and only does a full load every time. She says she doesn't use the tumble dryer as much.

Shower

Since the prepay meter was installed *'the lads have gone from half hour showers to 10 – 15 minutes in the shower'*. She is amazed by this turnaround.

Lights

All the down lighters in the kitchen have been replaced and she is delighted as she knew they were costly. She likes the energy saving bulbs.

Vents

Amy really does not like the newly installed vents because it causes draughts in the house and she can also hear noise coming from the street which she finds very annoying. She can hear people walking along the street, particularly late at night when it's relatively quiet. She now plans to block up at least some of the vents.

Defining Quote *'I'm delighted with the job'*

8.4 Dwelling D

8.4.1 Pre- upgrading Interview

Dwelling D is a mid-terrace, two storey semi-detached house orientated on a SE/NW axis. A flat roofed extension which is used as a utility room was added in the early 90's. Frank and Betty, both in their late 40's have lived in the house for 20 years. They have three adult children and two grandchildren. Their 18 year old son Patrick, a third level student, is still resident in the house. Their children and grandchildren visit almost every day and sometimes the grandchildren spend the night.

Frank was self-employed but, because of the recession, he is only working a few hours per week. Betty works irregular hours part-time as a carer. Consequently the house is occupied on an irregular basis. They describe themselves as not energy conscious *'if it's left on, so what'* and do not appear to actively partake in energy use saving techniques. The exception, however, is the washing machine. They say that they would be conscious about having a full load of washing. This is perhaps because they use the washing machine about four times a week. Frank had been very busy as a self-employed tiler prior to the economic crash but now was struggling to find work.

Standard of living

They describe their *'overall standard of living as good'* but feel that the house is a *'cold house because of the draughts if you got off the couch without socks or slippers your feet would freeze and the utility is a freeze box'*. The utility room is of flat roof construction and has minimal insulation and when the washing machine is used water vapour condensates on the walls and windows. They feel that lack of ventilation exacerbates this problem. Draughts come from the windows, doors, attic hatch, and the floor of the hot press which has a large hole. The windows are poorly fitted. Certain wind directions allow water to penetrate to the inside of the house. There is condensation on the windows because of lack of ventilation but they wouldn't open windows to reduce this. Frank says because of chronic health condition he feels the cold a lot. The sun in the morning reaches the front of the house and the rear in the afternoon.

Heating and hot water

When they moved into the house there was two open fires, one of these has a back boiler for the heating system. They decided to install a Stanley solid fuel cooker following installation of a new kitchen and tiled floor. This meant that they did not have to remove the new floor to install pipework for a gas system. A number of years ago the family were offered to change from their solid fuel stove to gas but again Betty didn't want the disruption of digging up all the floors and also said *'the gas seems to be increasing in price of it all the time'*. The cooker is connected to the central heating system which has no form of thermostatic control and can cost *'anything from €50 – 60 per week in hard weather and €40 per week in normal weather and that was taking it easy and not including the timber I got for nothing off farmers and around'....'smokeless coal is expensive'*. The kitchen and sitting room are interconnected by an arch and the open fire in the sitting room would usually not be used because they feel the cooker provides enough heat. Frank would also source some free timber (for free 3 – 4 trailer loads around 15 bags per trailer). The

immersion or kettle is used during the summer whilst during the winter the Stanley solid fuel cooker always provides hot water.

Utility Bills

Electricity is paid on a bi-monthly basis in the post office. They never usually examine their electricity bill but *'give out about it and pay it'*. Once or twice they compared their bills with their neighbours because they *'thought there was something wrong'*. They thought somebody had tampered with the meter.

Appliances

Cooking

There is a separate gas hob which is fuelled by bottled gas as well as an electric oven for cooking. The hob is usually used in the morning for breakfast and both hob and oven for dinner in the evening. The toaster is used mainly in the morning. The microwave is used for approximately fifteen minutes per day and a George Foreman grill is used on an irregular basis and *they 'got rid of the deep fat fryer'*. When asked about the electric kettle usage Betty replied *'the kettle is the biggest user in this house I'd say. It's used usually 7 or 8 but up to 10 times per day'*. The kettle is always filled before boiling regardless of quantity required.

Televisions/Phones

There is a 32" television and DVD player in the sitting room and this is on for about 8 hours per day but the DVD player is rarely used. Both are left on standby when not in use. Usually the grandchildren watch it during the day and it is then turned on again in the evening time. There are 14" TV's in each of the 3 bedrooms. Patrick watches TV and plays his games console for between 1 and 3 hours per day. The main bedroom TV is watched for about ½ hour each night, but sometimes Frank falls asleep and the TV is left on until morning. The 3rd is only used when the grandchildren stay. The radio in the kitchen is on about 4 or 5 hours per day. Patrick uses the laptop for at least 1 hour per day. Broadband is a prepay dongle.

Washing & Ironing

The washing machine is used at least four times per week, always with a full load and the cycle takes about 1 hour. When the washing machine is not in use, it is in a standby mode with an array of lights illuminated on the front. Betty says *'It can only be turned off if the plug is turned off'*. During the interview Patrick succeeds in turning off the washing machine by turning it to zero. This is the first time in 3 years it has been turned off. The tumble dryer is seldom used. Betty

irons almost every day to keep up with the washing. The dishwasher is used every day and the vacuum cleaner is also used every day on the timber and tiled floor.

Shower

The electric shower is used 15 – 30 minutes on average every day.

Lights

There is a single bulb in each room with only the bathroom light having an energy saving bulb because *'the energy saving ones kept blowing'*. The lights would often be left on in a room if moving to another room and bathroom or landing light would be left on most of the evening.

When the term fuel poverty was explained to Frank and Betty and they were asked – do you feel that you are fuel poor – *'By definition yes fuel does affect our standard of living in the winter'*.

Defining Quote: *'if it's left on, so what'*

8.4.2 Post- upgrading Interview

Standard of living

Betty instantly says *'it's great, the best thing that was ever done'*. She explained that the upgrading process was somewhat of an upheaval; scheduled for three weeks it took more than five. The contractor did not come to site every day and there was a lot of dirt and dust to clean up. The neighbours on each side also complained about the noise. The utility room is described as the warmest room in the house. It has had a new insulated roof, walls and radiator installed. The new gas boiler is also mounted in the utility room.

Frank says that his health has improved slightly because the house is warmer. He says the house is warmer but the new vents were causing problem, saying *'it was freezing' sitting under the vent in the sitting room. Now it's sealed with tape'*. The extractor fan in the bathroom is also turned off because it was too noisy and sealed and taped. They feel it was pointless installing the vent in the bathroom and having heating because of a back draught when the fan is off. They don't feel that the house is stuffy since the vents have been blocked up.

The newly installed windows and doors have reduced the levels of condensation considerably. The house is much cleaner and easier to keep clean because there is no dust from the coal. Each time the cooker was opened dust would float everywhere. Betty finds the newly installed wired smoke alarms very sensitive when cooking.

Heating and hot water

They availed of the option to install a prepay meter as part of the gas installation. Both are very happy with the system and top it up every week when doing the shopping whether they require it or not. They themselves are not in the house together often but they have friends and neighbours in and out all the time. Consequently they don't set the 7 day programmer and instead *'we use the one hour boost button when required'*. They turn it on for another hour again if they require more heating. The thermostat is set to 21 degrees but because the heating is on irregularly it's not used much. They don't programme for the morning. They don't see a benefit of the programmer for their lifestyle. They do like the boost button and they will feel the heat after 10 minutes. They expressed great satisfaction with the controllability of the heating compared to the solid fuel cooker. The central heating *'zoning is brilliant'* as that they can have hot water on its own. *'If you turn on the water in the morning, it's warm for the day'*. As a result, they don't have to boil the kettle for water anymore. Frank takes a bath most days to help his joints. Only two zones were achieved because the plumbing upstairs is linked to the sitting room since first being installed. This would require major works to rectify. The open fireplace was replaced with a stove which they *'often find too warm even with a small fire'*. Frank rarely lights the fire unless it's a very cold evening when he's not working.

Utility Bills

'The prepay gas is brilliant' but they have a concern that the electricity bill is still high. They say that the electricity usage has decreased a lot. Betty says *'now I'm watching everything'* they are more energy conscious as a by-product of the upgrading. They don't leave lights on in rooms that are not in use and they don't fill the kettle anymore. They plug out the television at night. Frank says *'they are only small little things'*. They say it's not an obligation *it's 'just what we do'* and when they see the reduction in the bills it acts as an incentive to continue.

Lights

Frank and Betty are amazed how long the energy saving light bulbs last *'we were always buying bulbs before..... we used to buy the cheap ones cause they were cheap..... we never bought the dear ones'*.

8.5 Dwelling E

8.5.1 Pre-upgrading Interview

Susan is an unemployed single mother in her early 30s and lives with her two young children in a mid-terraced 3 bedroom house. The house is clean but quite sparsely decorated. Susan spends most of her time in the house but when the kids are in school *would 'usually go down town between 9 and 1pm'*. Susan believes that she is reasonably energy conscious and does *'think about energy use but should do more'*. She doesn't think about the environment saying *'everybody else is looking after the environment so what can I do'*. She doesn't do anything consciously to save energy.

Standard of living

'It's quite a warm house'. She doesn't like the location of the house because there is general anti-social behaviour in the area. The house is just the right size for the two kids and she gets the sun in the front in the morning and the back in the evening.

Bills

Electricity and gas are paid by direct debit (DD). Consequently she never looks at the bill. She tries to budget but *'because the moneys there they just take it'*. *'I could save money easily if I thought about it'*.

Heating and hot water

She boils the kettle all the time for hot water unless the heating is on and never uses the immersion heater. She never uses a timer for the heating just turning it on and off as required. *'I would flick the heating on and the kettle and have a coffee'*.

Appliances

Cooking

The microwave is broken so Susan uses the electric cooker for breakfast and dinner, totalling about 1.5 hours per day. The kettle is boiled *'at least 10 times a day'*. The kettle is filled each time unless Susan is home alone when she only fills as required, suggesting that she knows she wastes water. Her toaster is broken, but she needs to get it fixed because she uses it in the morning.

Televisions/Phones

There is a 40" television in the sitting room and a portable television in the children's room so they can play PlayStation for not more than 1 hour per day. The sitting room TV is on between 7 and 10 hours every day and can be more if the kids are in the house. The kids get up early and can have it on 3 hours in the morning. They are always switched off at the wall at night. Her laptop is broken and she does not have broadband. She says that sometimes she will leave the room and leave appliances on. During the interview, conducted in the kitchen, the living room TV was on with no one watching it.

Buying appliances

Susan does not know what appliance ratings when purchasing. She said she *'had seen them but could never work it out'*. She chooses appliances by colour and if on offer but never energy rating.

Shower

The kids use the electric shower every second day and Susan is 15-20 minutes every day which adds up to 3 hours a week.

Washing & Ironing

Susan says that *'my washing machine has the longest wash ever; 205 minutes and can go twice some days, at least once every day but at the weekends twice'*. There is no tumble dryer in the house *'I hate them, because they ruin the clothes'*. She uses the line and an internal clothes horse in the kitchen. The iron is used rarely *'I don't iron much, I fold 'em'*.

Lights

There are a total of nine light bulbs in the house and only the sitting room has an energy saving bulb. The landing light is left on all night for security for the children. She likes the light tone from her energy saving bulb. *'Since I moved in none of the bulbs have gone so I have not bought any energy saving bulbs'*. Asked: Can you name the different light bulb types – *'No, they are just normal light bulbs'*.

Defining Quote: *'I never really thought about this stuff before to be honest'*

8.5.2 Post- upgrading Interview

The house was noticeably less well maintained than before the upgrading. The house seemed colder and the children had colds. There is also a new baby in the house.

Standard of living

'Everything's fine... it's definitely warmer in the morning with the insulation'. However, the gas was cut off in June before the upgrading because of non-payment of bills. They now only use the stove and two electric room heaters. Susan says *'it's not that bad'.* *'The stove is really nice and a lot of heat comes out of it'.* However, she is conscious that she needs to get the gas reconnected saying *'it's not fair on the children'.*

Bills

The electricity meter has been replaced with a prepay meter. She says that it seems to be cheaper and that the meter allows her to go into a negative balance over the weekend and she can top it up on Monday.

Heating and hot water

She uses the immersion to heat water for washing and the children. She says she hasn't a clue how much the immersion costs ... *'I don't think it costs that much'*

Appliances

She still leaves the TV on all day, but now only fills the kettle with the volume of water required. She just uses the cooker in the evening for dinner. The washing machine is still used every day.

Overall she is very happy with the upgrade *'but they ruined the carpet on the stairs'.*

8.6 Dwelling F

8.6.1 Pre- upgrading Interview

Ellie is in her late 50's and lives alone in her three bed semi-detached house. She has two sons, Jack in his 20's has his own apartment and Tomás, in his late teens, is in college and comes home most weekends. The house has a somewhat dated feel and the furniture is quite old and would benefit greatly from a redecoration. Ellie would classify herself as *'reasonably energy conscious.... even forgetting money, I think about the environment and waste.... I recycle'.* She leaves the TV and lights on if leaving the room to make a cup of tea or going up stairs. *'They say that it takes more electricity turn off and on things rather than just leaving them on for a short time'.* The

laptop is plugged in all the time *'because the battery is very bad in it....would that be using energy?'* *'I leave the bedside lamp on and fall asleep'*.

Standard of living

Ellie suffers from chronic health condition but doesn't believe the house contributes to the illness. Referring to her standard of living *'at the moment it's not very good anyway..... but the house is fine it's just me so overall it's fair I'm happy with the house, I'm not happy with the way I keep it all the time' 'I often said I'd like to take the house and move it somewhere else'*. The house is situated in a cul de sac with a large green in an area prone to anti-social behaviour. *'The house is big enough for my size of family I'd feel claustrophobic in a smaller house... even in a bungalow'*. *'I'd like to have a small extension in the kitchen and shower downstairs and a laundry room'*. *'Overall it is a warm house, everyone who comes in says it's warm and comfortable, especially with the windows'*.

Bills

She pays her electricity in the post-office when the bill arrives. Not long after installing the monitoring equipment Ellie converted the gas meter to prepay because it was free. She likes the system and finds it easy to use. She doesn't really examine her electricity bill but says *'there is so much VAT and levies'*.

Heating and hot water

Heating is provided form natural gas central heating which Ellie installed herself in 2002. *'I was fed up of the 2 fires and I suppose the gas company were fairly persistent and I wanted more heat and convenience'*. The heating is set to come on in the morning for a short while. She only lights the fire to air her clothes in the winter time.

She picks up waste timber around the area to burn in the fire. The hot press is used to air clothes, which they have always done. *'How would you dry clothes without it? People who dry their clothes in the kitchen, it's a disgrace and they would be getting the smell from the cooking'*. She uses the immersion heater for 15 or 20 minutes to heat the hot water when the gas heating is not on.

Appliances

Cooking

She uses the electric cooker usually 2 times per day to cook breakfast and dinner and she regularly bakes bread. Asked about the kettle usage she replies *'that would be the most often*

used I supposeemm probably about 6 or 8 times a day and late into the night'.. 'I tend to turn it on, then walk away, come back and turn it on again'. The kettle is often used for hot water for cooking vegetables.

Televisions/Phones

There are 4 standard tube TVs and two sky boxes in the house. There is a 20" in kitchen, a 32" sitting room and a 14" in each of the 2 main bedrooms. She watches the *'Dail session for about an hour in the morning'* in the kitchen and then moves to the sitting room and watches the larger TV *'for 6 hours at least'* every day. The bedroom TV's are used rarely. They are turned off but not plugged out at night. She listens to the radio for an hour or two per day. The sky box is left on standby so it can record programmes. There is landline and broadband and one mobile. The laptop is used for only an hour a week.

Buying appliances

When buying appliance Ellie only buys 'A' rating.

Shower

Electric shower usage varies *'in the real summer I'd have two some days but it isn't used every day... if I'm working round the house then I'd have one in the evening'*. The shower would be used more at the weekends when her son is home.

Washing & Ironing

The washing machine is used about twice a week *'I'd never put a half load on.... I've seen people put a pair of jeans in and oh my God it's mad'*. The tumble dryer is just used *'maybe for 10 minutes just to soften the towels'... 'sure the tumble dryer is a fierce cost for airing clothes and they burn out...how many fire has there been because of tumble dryers?'*. The dishwasher is used three or four times a week *'even though it mightn't be full because it gets smelly'*.

Lights

All the rooms have energy saving bulbs with the exception of the sitting room which has a cluster of 3 x 40W halogen bulbs. The light on the landing is left on in the evening until bed time. She has been using energy saving light bulbs since they first came out because saying *'I believe they save money in the long term'*.

Defining Quote: *'Does leaving stuff that's turned off plugged in use energy?'*

8.6.2 Post- upgrading Interview

Ellie finds that the house is far easier to heat since the upgrading. *'The new doors (front and rear) are great'*. She complains that sometimes it's too hot. When the new gas boiler was installed the programmer was set. Ellie does not know how to change the settings. Her son was present for the second interview. He assessed the programmer for the first time since installing and found it easy to understand. He then demonstrated how the boost button works.

Overall she says that she has not altered her energy use patterns. She never lights the new stove. She finds the new active vent in the bathroom a *'bit of a nuisance'*. *I always just open the window'*.

8.7 Dwelling G

8.7.1 Pre- upgrading Interview

Joanne, 35, lives with her two teenage children, Lorraine and Graham in a three bed mid terrace house. Joanne works part time in the mornings and her children attend school. The children only spend their evening and night in the house and are *'always on the go particularly in the summer'*. The house is occupied for on average of fourteen hours per day. Joanne is a smoker and has an unhealthy cough throughout the interview. The house has an overall dreary and unhealthy feel. Joanne says *'I'm reasonably energy conscious, cause I have energy saving bulbs and I plug out the TV'*. The two kids have asthma and sometimes have bad chests. Joanne does not believe that the environment of the house contributes to the asthma but it was worse before she got the gas central heating in 2008.

Standard of living

Joanne believes that the family have a good standard of living and likes the size and orientation of the house because the *'kitchen gets the sun in the morning'*. She describes the house as being *'warm'* and much better than before the gas heating and windows were fitted but *'the house goes cold quick when the heating is off'* and at *'night-time the house can get cold'* and during the winter *'I could rattle with cold'*. *'The wind blows through the front and back door'* and Joanne put a blanket across the front door to try to stop. *'I tried draught stripping before but did it all wrong'*. However, she is very hesitant to use the heating because of the cost.

Bills

She prepays €10 per week towards gas throughout the year and puts all the fuel allowance into her gas account in the post office. She also puts €10 per week towards her electricity year around

and pays the balance when the bill is sent *'I wouldn't have it (money) to pay it in full'*. Joanne doesn't like looking at the bills and does not examine them saying *'I just see the price and check that the money going in is there'*. *'I'm in credit on the gas so I don't look at it'*.

Heating and hot water

The gas central heating was installed by the council in 2008. The heating is set on timers usually set for 5 – 6 and 10 – 11pm during the winter and not usually in the morning. *'I love my fire and have to have it on every evening'* during the winter period. Asked if she thought it would it be cheaper to turn on the heating rather than burn coal she answers *'no..... I think the gas is very dear... I dread the heating bill coming through the door, I dread it'*. *'I panicked when they said they were putting it in (the gas heating)... straight away I just thought of the bill'*. If the heating isn't on *'the kettle is always used'* to provide hot water.

Appliances

Cooking

The electric cooker is usually used for evening tea and occasionally in the morning. The microwave is mostly used to heat up food. The toaster is not used every day. The kettle isn't used that much *'maybe once in the morning and once in the evening'*.

Fridge

There is a fridge and fridge freezer in the kitchen. Asked why they need a second fridge *'I need to keep the kids drinks cold'*. Opening the fridge door she revealed that the fridge is almost full of various drinks.

Televisions/Phones

There is a 32" TV in the sitting room and another in her son's room. Lorraine has a 14" TV in her room. Graham and Lorraine usually watch TV for a couple of hours per day. They do not have a games console. *'The TV in the sitting room is on all the time when I'm here..... even if I'm not watching it'*. The TV is *'only turned off when leaving the house'* and when turned off they plug it out.

Joanne has a laptop which she says *'I'm always on it.....mostly looking at facebook'* and between her and the kids is on for more than 6 hours a day on the internet which is a prepay dongle. Joanne surfs the internet for several hours per day while watching TV. Each occupant has a mobile phone and the plugs are always left plugged in. The two radios are used infrequently.

Buying appliances

Cost is the biggest driver when buying appliances followed by appearance. *'I never think about it being A rated'.*

Shower

In total the shower is on for 30 – 45 minutes *'it uses a lot of power so I have the kids warned'.*

Washing & Ironing

The washing machine is used almost every day, particularly to wash sports gear. There is no tumble dryer and she dries the clothes in the kitchen and hot press. The iron is used for about a half an hour per week on average.

Lights

The majority of the lights in the house are CFL bulbs with the exception of the landing and box room. *'they say that they save money cause they do last longer than the other ones'.* *'I'm waiting for the others to go and I'll replace them with energy saving bulbs'.* The light in the bathroom hasn't worked in a few months because of a wiring problem. Joanne is waiting for the council to fix it. Asked if lights are left on unnecessarily *'always'.... 'we leave lights on all over the place'.* The light in the hall is left on all night *'for security, shows there's someone in the house and for the kids'.*

Asked: Can you name the different light bulb types – *'No.... They are just light bulbs'.*

Asked if things are left on unnecessarily: e.g. leave lights and TV when going to cook the dinner *'You'd look well coming in to cook the dinner and turning everything off in the sitting room.... Why would ya?'*

Defining Quote: *'I'm at the bottom of the pile saving energy'*

8.7.2 Post- upgrading Interview

Standard of living

The house is much cleaner and better maintained than at the time of the first interview. Joanne finds the house much warmer since the upgrading. Replacing the front and rear doors has made a big difference because there are no draughts. Looking at the thermostat in the kitchen she says *'the highest I have ever seen it is 18.5⁰'.*

Heating and hot water

Joanne turns on the heating only as required. She uses the one hour boost saying *'I don't know how to set the timer'*. The heating is never used the morning. She says she very rarely uses the gas anymore. She was able to set the timer before the upgrading and used it more often. Joanne says *'the new stove is brilliant'* and she leaves the door in the sitting room open allowing the heat permeate the whole house. The stove burns far less coal and she uses a 20kg bag of coal per week only. She still boils the kettle to heat the water because she finds that using the gas to heat the water only takes a long time. She still puts the €10 per week towards each of her utility bills.

Appliances

She does not really have a concept of which appliances use the most energy saying that her kids do spend a lot of time in the shower. However, because of her weekly energy budget she does not think about energy. She is just happy she doesn't get a bill.

Airtightness/Vent

She does not like the newly installed passive vents. She can feel a cold breeze at her head because of the location of her bed. Through the vent in the sitting room *'I can hear everything happening outside. Before the upgrading it was stuffed with a rag..... I'll stuff both of them again'*. Joanne explains that because the fan in the bathroom is connected to the light switch when taking a shower during the day without the lights on the fan doesn't come on.

Overall the project took a little longer than expected.

8.8 Dwelling H

8.8.1 Pre-upgrading Interview

Alison, 66, lives alone in a house that is identical layout to Dwelling J. The house is mid terrace and is decorated and maintained to a high standard. New double glazed windows, timber doors and gas central heating were installed in 2007. Her grandchildren stay over two nights a week and visit regularly for their evening tea. She works part time from 7:30am – 1:30pm in a local school and walks into town for an hour or two a couple of times a week. Alison receives an annual electricity allowance (under the disability scheme) and fuel allowance in the winter. She prepays €10 towards her gas every week in the post office and she does not go over her electricity allowance and consequently has not paid an electricity bill for 4 years. She doesn't consciously save energy to be within her allowance *'it's just the way it works out'*.

Standard of living

She thinks she has a *'good standard of living'* and likes the size of the house and location. However, she describes the house as *'a cold house.. I don't know why... but when the sun comes around to the back in the evening it can be lovely'*. Later she goes on to say *'well I've always been a cold person.... My friend comes over and the house is too hot for her'*.

Bills

She pays little attention to the bills.

Heating and hot water

Heating and hot water are produced by the gas boiler and central heating. The boiler has a timer and if she is not in the house *'it will come on and stay on, if I was here I'd turn it off when it gets warm'*. The open fire is lit every day in the winter from when she gets home from work and from time to time in the summer. She uses the timber *'because it would save a bit on the coal'*. When the heating isn't on during the summer *'I leave the immersion on, on the sink setting and that does me for a bath in the summer'*. She uses her electric blanket for ½ an hour every night during the winter.

Appliances

Cooking

Alison uses her electric cooker *'about 4 times per week..... maybe Sunday lunch for the kids and a few tarts during the week..... I'm not a big eater'*. She doesn't have a microwave. She boils the kettle about three times a day.

Televisions/Phones

She has a 26" television in the main bedroom and a new 32" flatscreen in the sitting room. She says *'the TV goes on when I get up and goes off when I go to bed....sometimes I won't be watching' it but it would still be on'*. The television in the bedroom is seldom used. She always used to turn off the television completely but she doesn't know how on her new flat screen so it remains on standby. She does turn off the skybox.

Shower

She doesn't have a shower, though she would like one. She has a bath every day.

Washing & Ironing

She usually does three clothes washes per week or when she has a full load. The washing machine has an integrated tumble dryer which is always used to dry the clothes. She irons for about ½ hour per week. The whole house is vacuumed 3 or 4 times a week.

Lights

With the exception of the florescent bulb in the kitchen all the bulbs in the house are 'ordinary' incandescent bulbs. All lights are turned off as she leaves the room and a light is not left on at night.

She doesn't have any other energy saving bulbs *'because they are too dim to start...I got an energy saving bulb for the hall a few years ago and I had to take it out again, because I couldn't see a thing'..... 'if you turn them on for a while it brightens up, but I would only be getting a phone number or something'.*

Defining Quote 'I love my fire'

8.8.2 Post- upgrading Interview

Alison finds there to be a big improvement in the comfort of the house. *'Before I would have the fire on and have to turn on the gas for the bedrooms, now I don't'.* She elaborates by saying that she only uses the gas from 6:30 to 7:30am and when she leaves the sitting room door open the new stove can heat the whole house. The central heating programmer was set by the installers who showed her how to use the boost button if it gets cold. She still uses the immersion for less than an hour for hot water so she can bath. She still lights the stove everyday just for comfort.

Bills

Alison still pays €10 per week towards her gas and electricity. At the time of the interview she was overpaid by €150 which gives her some comfort.

Overall Alison is very happy with the upgrading but says when the wind comes from a particular direction *'there's a little whistle for the new vent'.*

8.9 Dwelling J

8.9.1 Pre- upgrading Interview

Joe and Marie a retired couple in their early sixties live in a two bedroom, single storey semi-detached house built in 1986. At approximately 50m² the house is compact consisting of a kitchen/sitting room, two bedrooms, bathroom and hallway. The house is very clean but has a

dated décor. Marie says with a laugh *'we live very simply'*. Marie suffers from chronic health condition and finds it difficult to move around. She is constantly cold which is why the heating is constantly on and temperature very high. Joe believes the dwelling environment contributes to the illness because the humidity is so high, but Marie disagrees blaming Kilkenny itself *'Kilkenny sits in a kind of bowl.... and it's damp all the time'*. Marie rarely leaves the house and Joe is absent not more than two hours per day to run errands. They class themselves as being *'reasonably energy conscious'*. *'We are careful by only filling the kettle as required, waiting for full load of washing, we always keep external doors closed.. if someone calls to the door we nearly always invite them in rather than have them stand there with the door open'*.

Standard of living

They like the location of the house and believe their standard of living is *'very good'*. *'The sun shines in here the whole day'*. The house is large enough for the two of them but they wish they had a bigger kitchen. They classify the house as being warm because it has a good heating system and good windows which were installed in 2005. *'It's a fine house and always lovely and warm'*. Condensation occurs throughout the house as a result of cooking and bathing. *'It's condensation from the cooking You can see stripes down the wall'*. They understand it's not dampness but don't do anything to prevent it *'we should have an extractor fan, but we can't afford it'*. *We don't open windows even when in the bath'* to keep the heat in.

Bills

They pay their electricity and gas as it arrives in the post office.

Heating and hot water

The gas boiler which is mounted on the wall in the sitting room provides all their heating and hot water and is on a timer. A timer is set for the morning but it is then turned on/off manually during the day. Sometime the heating goes for five hours without turning it off. They never use the immersion. Joe says *'that (immersion) and the kettle are the worse'* for energy use. The fireplace is blocked up with a plastic bag because they just use the heating system all the time.

Appliances

Cooking

They have an old style electric cooker that is used at most once per day for approximately 45 minutes to cook the evening meal. The microwave is not used every day. The kettle is boiled 3 or 4 times a day. Joe says *'we only put in a little drop of water in the kettle'*.

Televisions/Phones

They have an old style 28" tube television in the sitting room. They watch the news at 1pm and then turn it off until 5 when it's on until 12 midnight before bed. The TV and sky box are left on standby when not in use. Joe says *'I got a video for nothing but it's not connected up'*. They listen to it at most 4 hours per day and turn it off when done.

Shower

They do not have a shower and use the shower head attached to the taps on the bath. They have approached the LA on a number of occasions to get the bath replaced with a disabled shower but have been turned down. Joe says *'it's terrible, they gave us a chair for Marie to sit on in the bath, but she can't get into it, it's brutal'*.

Washing & Ironing

The washing machine is used once to twice per week and they always use the tumble dryer. They avoid most of the ironing by buying easy care clothes. The vacuum is used once a week for 10 minutes.

Lights

There is a low energy bulb in the hall. The sitting room light is not used but there are two side lamps with energy saving bulbs. The kitchen has a small florescent bulb under the counter. There is a low energy one in the bathroom. The spare bedroom is seldom use so they only have ordinary bulbs. They always turn off lights when not using a room *'if we're in here (sitting room) there will be no light on anywhere else'*. They do not leave any lights on at night.

Do low energy light bulbs save money? Joe says *'we're only going by what they say and they say they do.... I know they last longer... if a 60W bulb is only 14W they must do'* and they believe they are value for money.

Defining Quote: *'we never leave anything on when it's not being used'*.

8.9.2 Post- upgrading Interview

There is a huge difference in the house *'it's a great job'*. They have the thermostat set to 24°C and say *'the temperature has never dropped below 20.5°C'*. Joe finds the seven day programmer great. He explains that he has the programme set for hot water only every morning. He uses the boost button for heating when required. *'We never use the automatic heating, because we are always here'*. During the upgrade a new gas fire was installed to replace the existing one. Joe explains that they never use the fire and asked that the whole unit be permanently sealed but the

contractor persisted. Both are very happy with the new front and rear doors and the new extractor fan in the kitchen. The contractor was due to complete the project in 3 weeks but Joe explains that it took nearly 2 months to complete *'because they were doing bits and pieces'*.

They express their dissatisfaction with the two new vents that were installed. Marie says the new low level vent behind the couch *'causes an awful draught, but I'm always cold anyway'*. Joe says *'I'm going to put some tape over it'*. They say they still function the same way as always and have not changed any other behaviour.

8.10 Conclusions

A central tenet of this section was to gain an insight into occupants' habits namely what they actually did and also of their perception; what they thought of their energy consumption. The interviews provide information that helps to fill the gaps in knowledge surrounding the reason for the large variability in measured energy consumption. The opinions of the occupants are important and were valued by the researcher. The coding methodology used identified trends in the information gathered as part of the interviews as well as documenting casual observations. Individual household consumption varied greatly and by their nature was affected by psychological, habitual and social structures. The following sections summarise some generalised findings which were consistent amongst the occupants.

As stated earlier, the general perception that the researcher got was that, in overall terms, the occupants were very happy with the results of the upgrading. This section now discusses some of the more salient findings. Section 6.8 highlights that there is only a nominal reduction in electrical consumption over the summer. This is unusual as it would be the norm that household bills would decrease dramatically over the summer. However, the interviews and observations revealed that the occupants tend to have a sedentary lifestyle thus spending considerable amounts of time in their homes and have habits that they appear to have followed for years. Many have a routine of watching particular programmes every day, or leaving the TV on when no one is watching it. Many developed these habits and routines in their own childhood, continued into their adult life and have been passing these habits on to their children. In general, because most don't go out to work they spend a lot of time in their house and hence high electricity bills even in the summer.

A small proportion of the occupants were generally aware of their energy consumption and considered themselves to be quite energy conscious, whilst others were not at all either interested or aware of their energy usage. Most complained about their high energy bills but did little to address the issue. There were some unusual traits amongst a small number of occupants.

Some turned on the electric shower in the bathroom to heat the room prior to taking their showers. Perhaps this is a habit developed when there was no central heating in the bathroom but it is an obvious waste of energy.

A number of households thought that their electricity was cheaper at night and used the immersion heater for extended periods. None of the households had nightsaver electricity and are not getting the benefit.

Perceptions of appliances that were heavy energy users

There are clear energy use perception gaps that exist even amongst people of the same social class. In general, the occupants did not seem to understand what appliances used most energy. Some thought the laptops, some thought lights and others the electric kettle. Others gave the impression they were guessing. They also weren't generally aware of different types of lighting and their energy usage. It is therefore important that people with technical knowledge don't assume equal knowledge levels amongst occupants. Occupants appeared more likely to take advice from someone they respected for example, a family member or neighbour than from a technical expert. When buying appliances they were aware to some extent of the energy ratings on appliances. However, most choose to buy on price and didn't seem to realise that they would pay more over the lifetime of the machine because of the higher energy use.

Heating System

Most found setting the newly installed seven day heating programmer too complex. In fact they just used the one hour boost feature as required and this was a feature they liked. Not all occupants were au fait with the zoning feature of the system. Though awarded savings as part of the DEAP methodology it is clear that without detailed tuition those occupants are not able to avail of the benefits the upgraded system offers. In reality, these added features became defunct.

Ventilation

These were the single aspect of the upgrading, which across the board, were disliked by the occupants. They did not understand the need for vents and when mentioned, they were consistently talked of as being noisy, annoying and draughty. A number already had and more were going to close up their vents once the study period was complete. Section 7.5 deals with this occupant feedback in more detail. This is an area that needs to be examined in detail for future energy upgrades. Most occupants did not understand the importance of good ventilation. The consequence of poor ventilation was witnessed in dwelling J where air quality was poor and condensation was evident on internal walls. As with the heating controls system, the vents are required to comply with the building regulations. However, this study shows there appears to be

little point in spending time and money on installing ventilation systems that will be decommissioned or blocked off.

Pre-paying energy bills

There appeared to be a certain level of in-built trepidation across the board in relation to paying utility bills. Perhaps, this was in their psyche because of their own prior experiences of their supply (or their parents supply) being cut off in the past. Most occupants prepay a fixed amount each week year around. They overpay their gas bill in the summer which helps builds a reserve over the winter heating season. The recent roll out of prepay meters became popular amongst the occupants. Even, though there is a charge with a number of the private prepay meter operators a number of occupants either had or were planning to avail of this service.

Unintended Consequences:

There appeared to be some unexpected benefits. Some of the teenagers living in the houses appeared to change their energy use behaviour. In the interviews, this change in behaviour was attributed to them observing the meters and in general being more energy aware.

The Stove

The inclusion of the new stove in the upgrading appeared to be what the occupants considered to be the best aspect of the upgrading. The occupants reported that they consume the same amount of fuel but the heat generation is much improved. If anything, the model supplied was probably too powerful for the small sitting rooms. The occupants of dwellings G and H reported that they now leave the sitting room door upon to allow the warm air circulate around the whole house. This can be attributed to the very large reduction in measured gas consumption.

Summary

An integral aim of this work was to research *with* the occupants rather than just *about* them. The researcher was keen to explore the occupants' lifestyle patterns and attitudes and how this impacted on their energy use. This chapter has outlined the key findings from the interviews in an effort to establish how human behaviour impacts on energy use.

Chapter 9

9 Conclusions

This chapter summarises the combined conclusions of the individual chapters. Each of the aims and objectives are revisited and reviewed to assess if they have been achieved. Firstly, this section gives a brief summary of the study followed by an explanation of the methodology used. The chapter goes on to address how the key findings, aims, and objectives provide an original contribution to knowledge. Finally, proposals for future studies are presented.

9.1.1 Summary

The residential sector accounts for approximately 27% of all primary energy used in Ireland. Considerable energy savings can be achieved as this housing stock has been identified as being one of the least energy efficient in the EU-27. The EU Action Plan for Energy Efficiency states the residential sector can cost effectively reduce energy use by 27% and the majority of these savings can be made by upgrading the existing residential housing stock. The Irish Government is strategically investing in energy efficiency upgrading programmes, such as SHIP, in an attempt to substantially reduce energy consumption and associated carbon emissions from the residential sector.

Chapter two presented a comprehensive literature review of previous research completed in the field of energy efficient upgrading in the residential sector. The review found that residential building energy performance and the benefits of energy efficient upgrading is predominately measured using quasi-steady state methodologies that only assess technical outcomes. However, dwelling energy consumption encompasses a complex interdependence of many quasi-steady state and highly dynamic conditions, including building fabric, external climate and occupant activities. How each contributing factor interacts is poorly understood in many cases. This often leads to a performance gap between actual and predicted energy consumption. The review concluded that there is a lack of evidence based research to demonstrate energy use patterns and actual benefit of energy efficient upgrading in the residential sector. This evidence-based multidisciplinary methodology was designed with the following aims to address the gap in knowledge highlighted in the study.

9.1.2 Aims

There were two key stated aims to this research. This first aim was to add to the body of knowledge about actual domestic energy consumption and evaluate the benefit of energy efficient upgrading of Social Housing in Ireland using an evidence based approach. Secondly, the researcher proposed to use these findings to make recommendations informing stakeholders and

policy makers with the necessary data and knowledge to improve the outcomes of energy efficient upgrade schemes.

A number of research strategies were utilised in this research to fulfil the aims and objectives of the study. The preliminary field study in Waterford involved BER's and airtightness testing of twenty eight single family homes across three age ranges. This added to the knowledge about domestic energy consumption. Here the researcher also gained fieldwork experience and developed strategies about engaging and enhancing relationships with social housing tenants. The study allowed appropriate mechanisms to appraise the suitability of tenants for the main study in Kilkenny. The study also offered the researcher time to develop the skills and knowledge required to carry out the technical aspects of the BER's and airtightness testing.

Kilkenny County Council (KCC) wished to evaluate, in depth, the actual benefits of their upgrading practices with a view to become exemplars to other local authorities involved in upgrading works. As a result, KCC agreed to support the longitudinal study and provide capital funding for monitoring equipment. Consideration had to be given to the security of this expensive equipment. Therefore, care was taken in the selection process to mitigate against the potential for the equipment to be damaged or removed. Following an intensive desk study and a large number of consultation meetings with the stakeholders, nine households willing to partake in the study from those scheduled to be upgraded were deemed to be suitable. This was a limitation of the study in that the dwellings selected were not representative of all social housing in nationally. This was outside the control of the researcher as the council were only willing to invest money into upgrading where they deemed they would get the co-operation of the tenants.

For this study a predominantly quantitative methodology was adopted to gather the empirical data required for subsequent analysis to establish the effect of energy efficient upgrading. This was followed up by a qualitative study which examined how human behaviour affected energy use. It also evaluated personal experiences as a result of the energy efficient upgrading using a combination of ethnography, phenomenology and semi-structured interviews. The researcher comes from a technical background so it was particularly important to try and understand how the habits of the occupants being interviewed actually did affect energy use and understood and apply their knowledge of energy usage. '*Within method triangulation*' was an important aspect of this mixed method research and the study adopted the principles of the '*Triple Bottom Line of Sustainability*', as discussed in Section 3.1.

The upgrading strategy was developed to comply with the eligible works under SHIP and focused on improving building fabric, primary and secondary heating systems and controls. The DEAP software tool was used to determine the relative energy efficiency benefits of various design improvements. A matrix of potential upgrading interventions led to the development an optimal upgrading strategy for each of the dwellings.

This study now restates the aims and objectives of the study and discusses findings relevant to this section.

Aim 1 of the Study

This aim was to add to the body of knowledge about actual domestic energy consumption and evaluate the benefit of energy efficient upgrading of Social Housing in Ireland using an evidence based approach.

This aim was achieved through objective 1, 2, 3 and 4.

Objectives

- 1. To review the present body knowledge surrounding relevant aspects of domestic energy consumption in the social residential housing sector;*

This was comprehensively dealt with in the literature review and throughout the document. The success of energy efficient upgrading of social housing traditionally has been measured by technical means using quasi-steady state energy performance methodologies. This research has shown that dwelling energy consumption encompasses a complex independence of many quasi-steady state and highly dynamic conditions including building fabric, external climate and occupant activities. How each factor interacts is poorly understood in many cases. Existing methodologies lack a formal evidenced based approach and rely on simplified models which use limited input data. The review also critically examined the findings to identify the performance gap between real and predicted energy consumption.

Two key facts stand out. Firstly, there is a lack of evidence based research to demonstrate energy use patterns and actual benefit of energy efficient upgrading in the residential sector. Secondly, the impact of occupant behaviour is poorly understood as dwellings with similar characteristics and occupant profiles having very different energy usage.

2. Develop and implement a methodology to remotely monitor dwelling energy use and environmental conditions.

DEAP only gives an estimate of dwelling energy performance which is independent of specific climate and occupant characteristics. It is necessary to determine the actual energy use in the dwellings to evaluate the actual benefit of energy efficient upgrading in a dwelling. A key aspect of the study was to minimise influence on occupant behaviour. Hence, the monitoring system had to be robust, report externally and remotely for at least one year pre- and one year post-upgrading to minimise the influence on occupant's behaviour.

An extensive review of existing technologies found that there is no 'off-the-shelf' remote energy monitoring systems or established protocols designed for domestic sector. The researcher attempted to design a bespoke system to remotely monitor the required dwelling energy use parameters and environmental conditions. However, this involved dealing with a limited budget and external design consultants. The system was designed to locally log gas and electricity usage, indoor temperature, humidity, air quality and external environmental conditions every fifteen minutes in each dwelling. The data was then remotely transferred to a secure database for subsequent analysis. The design, production, installation and calibration of the system took over two years.

Chapters 3 and 4 have outlined the reliability issues with monitored energy data and the reasons why this design was not fit for purpose for this research. This was a serious disappointment for the researcher. However, sometimes you can learn more from your failures than successes. Fortunately as part of the calibration process, gas and electricity meter data was recorded on a regular basis. This physical data collection was continued for the 36 month duration of the pre- and post- upgrading monitoring phase of the project.

The researcher was asked to get involved in a similar project in Dundalk and felt that the lessons learned and knowledge gained was of value for the design of a more robust system to meet their needs. The researcher has subsequently learned that even the system installed in Dundalk has a number of ongoing issues with data quality and transmission. This highlights the complexity of implementing a remote energy monitoring system in the residential sector.

3. *Compare real monitored data with predicted Building Energy Rating (BER) energy consumption;*

DEAP is the official methodology to verify energy savings under the SHIP programme. To ensure a like for like comparison the theoretical delivered energy components of the space and water heating (SWH) were extracted from the final BER results and compared with the measured SWH consumption. This study found that the average measured energy consumption pre- and post-upgrading was 60% and 72% respectively of the theoretical energy predicted by DEAP for the nine dwellings. This is contrary to some previous empirical research. It may also be hypothesised that social housing tenants have less disposable income and may not be able to heat their homes to a comfortable level. However, this cannot be proven and none of the occupants considered themselves as 'fuel poor' when asked in the interview. There were a number of outliers. Considerable reductions in energy consumption post-upgrading were observed in some cases. This could not be explained by either the DEAP methodology or the measured data.

DEAP calculates performance independently of the individual characteristics and uses standardised assumptions relating to occupancy and heating parameters. Therefore, at best DEAP can only give an estimate of real energy performance. This section did not provide an in-depth analysis of the DEAP assessment criteria but highlights the trade-off between accuracy and simplified calculation procedure. Though DEAP results may be representative of national domestic energy use, the model is inaccurate at a micro level leading a performance gap and cynicism amongst occupants about the usefulness of the methodology.

The SHIP programme used BER's to verify energy savings on an individual dwelling level. The study therefore raises the question about validity of the DEAP methodology to accurately assess energy savings for upgrading schemes, such as SHIP. The findings suggest that a more robust, reliable and defensible methodology be developed specifically for the Irish region.

4. *Evaluate the effect of energy efficient upgrading using socio technical inputs taking into account the profiles of occupant characteristics and physical dwelling parameters to quantify actual energy savings;*

While a visual summary approach is useful to identify trends in data, the methodology relies heavily on the analyst's knowledge to be able to interpret what is being presented. To improve the observation robustness the use of mathematical and statistical indicators can help to inform the judgements.

Degree days are considered to be a versatile climate indicator and a good reference point against which energy consumption can be measured. Degree days offer a simplified approach to balance heat gains in buildings. Other methodologies such as DEAP use steady state utilisation factors to balance these gains. However, DEAP cannot account for discrete geographical climate variables. HDD for this study were obtained from a weather station within a 4km radius of dwellings. The study utilised the 'performance line model' which is commonly used for M&V. The performance line is generated as the linear relationship between energy consumption plotted on y-axis and degree days plotted in the x-axis. A degree day ratio-based weather correction was applied to the data to allow inter-annual energy consumption comparison. A statistical review of the data shows that largely there is a good correlation between SWH consumption and HDD. However, the study confirms that this methodology is not suitable for short term, such as inter-day, analysis. The analysis shows that it is particularly difficult to calculate a baseload for individual dwellings. Comparing consumption for a 'normal year', revealed an average 47% reduction in SWH energy consumption following the upgrading. The analysis revealed a large variability in SWH consumption between dwellings that have very similar physical and occupant characteristics. This highlights that considerable care needs to be taken when making conclusions about SWH usage and trends and signals the importance of taking individual occupant behaviour characteristics into account. One such trend was that considerable variation in pre- and post-upgrade SWH consumption usage and trends in dwellings G, H and F. It was found that the occupants had simply changed their behaviour in two of the cases and used the increased efficiency of the new sitting stoves to heat the whole house.

The study found that the electricity consumption was stochastic in nature with peaks and troughs evident for no obviously apparent reason. There was an average marginal decrease in electricity consumption, of 7.5%, and some of the dwellings actually increased their consumption. This is not surprising as the only improvement to the electrical system was the installation of energy efficient lighting. Unlike SWH energy consumption, which peaked during the winter there was only a nominal reduction in electricity consumption during the summer period.

The interviews and observations revealed that the majority of the occupants in the study were not working. They also lead a predominantly sedentary lifestyle thus spending considerable amounts of time in their homes. They have habits and daily routines like watching particular programmes every day, or leaving the TV on when no one is watching it.

Assessing SWH and electricity consumption in isolation carries the risk that if one reduces the other may increase. This study has shown that overall combined SWH and electricity energy savings for a 'normal year' reduced by 67 kWh/m²/yr. This represents an average annual kWh saving of 33%. In monetary terms this equates to a current saving of approximately €410 per annum. This is obviously very welcome for the occupants who did not have to invest in the upgrading themselves. However, the payback period is estimated on average to be approximately 24 years. Without considerable subsidies this return on investment upgrading would not be an attract proposition for private homeowners who would have to fund the upgrading themselves.

The study found a weak correlation between energy consumption, floor area and income. If the occupant profiles were less homogenous it could be expected that income and occupancy would have a greater influence on consumption. The variability the results demonstrate that there is not a linear relationship between the level of technical energy efficient upgrading and energy use. For this relatively homogenous dwelling type the results suggest that occupant behaviour and perception play a large role in energy use and that this behaviour is affected by cultural, habitual, psychological and economic inputs.

A prominent feature of the study was that occupants budgeted for energy on a short term basis by pre paying on weekly basis. They did not analyse their bi-monthly bills and were content if there was sufficient funds built up to meet the bill. In fact, a number of the households over budgeted for their bills and had money lying dormant in the accounts. A number also change to prepay gas and electricity meters. All of the people who changed over express satisfaction with this option and it would appear prudent that they become standard in all social housing as an aid to budgeting for energy costs.

Heat loss from buildings occurs predominantly through the building fabric and through ventilation and infiltration. This section tries to estimate the proportion of infiltration heat loss occurs in each of the houses. Also during the interviews the occupants expressed dissatisfaction with the newly installed passive and active vents.

The study showed that the DEAP 'structural airtightness' methodology does not apply adequate energy savings by improving airtightness. Hence, upgrading strategies largely ignore the potential of envelope tightening to reduce energy consumption. Superficially each dwelling, by type, was identical but standard blower door testing revealed a large variability in envelope airtightness. Interestingly, an unintentional co-benefit of standard upgrading was a significant improvement in envelope airtightness. Average airtightness levels increased by 22%. Notably, post- upgrading, 66% of the dwellings were more airtight than the DEAP estimated. The results from the weather-dependent model demonstrated that air infiltration plays a large role in the energy performance of dwellings. Using the measured performance of the dwelling for a 'normal year' the average proportional infiltration heat loss pre- and post- upgrading equates too approximately to 14% and 20%, respectively, of the dwellings heat load. As fabric heat loss is reduced the proportion of infiltration heat loss increases. Achieving high levels of airtightness is challenging in existing dwelling but tangible reductions in energy consumption can be achieved by actively improving airtightness, often through inexpensive interventions.

Overall, the results were positive but the quantitative data could not explain the reason *why* there was such variability in energy consumption between a homogeneous housing stock and occupancy profile. The qualitative research therefore was an integral part of the research. This phase revealed the occupants lifestyle patterns, attitudes and how this impacted on their energy use. This element of the study is not to offer a complete understanding of human behaviour and exactly the reasons why energy use is so variable. The interviews do help to fill the gaps in knowledge surrounding the reason for the large variability in measured energy consumption. The process found trends in peoples' approach and attitudes to energy. Overall, this part of the study didn't uncover every nuance of energy use in each of the dwellings but did highlight the interconnectedness of a myriad of variables.

Aim 2 of the Study

The researcher proposed to use these findings to make recommendations informing stakeholders and policy makers with the necessary data and knowledge to improve the outcomes of energy efficient upgrade schemes and transfer national housing stock.

This aim was achieved through objective 5.

Objective

- 5. Examine upgrading successes, barriers and identify the potential to improve the outcomes of energy efficient upgrading schemes.*

This research adopted a multidisciplinary approach combining an examination of fundamental engineering principles as well as examining the impact of occupant behaviour on energy use. A success of the upgrading programme was that significant savings were achieved and overall occupants were happy with the process and found their homes to be more comfortable. There were a number of occupants who appeared to become more energy aware following the upgrading. Similarly, an unintended consequence was that some of the dwelling occupants who were not bill payers and who the bill payers found to be nonchalant about energy use (usually adolescent children) actually observed the prepay meter and as a result also changed their behaviour to become more energy aware e.g. taking shorter showers.

One unexpected barrier the researcher found was that occupants often base their decisions on the advice of someone who is not a technical expert in the area e.g. a family member or neighbour. This led to misinformation about peak energy users in the dwellings.

Most occupants found setting the seven day heating programmer too complex to use. It turned out the occupants just used the one hour boost feature when required. It is important that installation technicians spend longer showing occupants how to use such technology. It is also important that they call back after the installation to check if it is being used properly or to help the occupants to get to grips with correct use of the technology. The occupants felt that the technicians were always in a rush to their next job so companies need to factor in considerably more training time in the technicians' schedule.

The proportion of energy use attributed to airtightness increases as building fabric is upgraded. Further research is required to improved accuracy of simple predictive airtightness and energy models for Irish dwellings. The first step along this path is to undertake and formally collate wide scale airtightness testing. Airtightness testing should be encouraged where all fabric upgrading occurs to maximize energy savings credits. The DEAP software tool should be updated to more accurately reflect actual infiltration energy heat loss. This will encourage designers to include airtightness as part of the upgrading strategy. If done to a high standard the industry should see a move towards demand control ventilation or HRV systems which will maintain good air quality for the occupants.

The researcher has built a good working relationship with members of the KCC Local Authority housing technical team. A reoccurring issue arose during several meetings and conversations with this group. In a number of cases where the LA have upgraded dwellings, due to the occurrence of cold bridging and/or lack of adequate ventilation, incidences of condensation and mould growth are common. This was a feature reported as under ventilation in dwelling J of this study. The researcher visited a number of sites unrelated to this study where the problem was more pronounced. The suggested solution was to retrofit with a demand control ventilation system which is triggered by CO₂ or moisture sensors.

Occupants found the newly installed or cleaned out vents annoying, noisy and draughty. In many cases, these vents either already were or were going to be sealed by the occupants. This is an area that needs to be examined in detail for future energy upgrades. There appears to be little point in spending time and money on something that is not seen to be effective by the end consumers. A public awareness campaign is needed to encourage the usage of vents and to increase awareness of their value.

The people in this study availed of the upgrading at no cost to themselves. The technology works but it is unlikely that the private householder, particularly in a recessionary period of the economic cycle, is going to invest where the payback period is of this magnitude (estimated to be over 20 years). Therefore the options open to the policy makers is either to extend the range of subsidies available or secondly, to incentivise the householders to upgrade. One possible incentive could be linked directly to property tax and the BER rating. The bands of tax could be calculated just like motor tax with less efficient dwellings having a higher tax band.

The technical findings of this research could be used to inform stakeholders like the Department of the Environment, Community and Local Government and the SEAI of the actual evidence based impact of the upgrading. This study allows for the findings to be presented in a clear and concise manner.

Based on the previous findings there needs to be a paradigm shift away from a belief that purely technical upgrading of a dwellings' fabric and services can yield the required results to meet our 2020 and 2050 targets. Policies need to be developed that include targeting occupant behaviour and increasing their awareness about wasteful energy use. Simple processes like turning off unused appliances and not using the electric shower to heat the bathroom can result in sizeable reductions in electricity consumption.

In the view of the occupants there was considerable disquiet in relation to both the quality of the workmanship and the stop-start nature of the contractors. It was quite common that they were told that the work would take not more than five weeks. In most cases the contractors went over time. To improve the outcomes works should be completed in good time. It is also imperative that regular inspections of the quality of the work be undertaken but by a qualified and competent officer as the researcher found some evidence of shoddy work which would not be picked up by the occupants. The researcher suggests that a proportion of the allocated funding is ring fenced for the provision of inspection personnel to ensure that all works are carried out in accordance with the design specification and in line with best practice.

Designers need to explore the relationship people have with their homes and understand their perceptions of dwelling adaptation on their quality of life. Overall the occupants seem happier with their new front door from an aesthetic viewpoint rather than impact on energy use and comfort. To maximize the benefits of upgrading it is clear that there should be multiple liaison sessions with occupants before, during and after works to ensure they understand why a particular process was carried out, whether regulatory or voluntary, and how to correctly deal with any new systems or processes.

There are still gaps in the knowledge particularly pertaining to 'how' to effectively influence occupant behaviour in a manner to save energy. The researcher has built up a good rapport with the tenants and future Action Based research projects will continue in Kilkenny. The researcher will provide feedback from this study and offer advice on how to become more energy efficient. Any change in consumption will be captured in the metered data. Later the intention is to offer training to these tenants who will then disseminate the information throughout their community. The impact of this task will be assessed through local focus groups.

9.1.3 Triple Bottom Line

This study sought to embrace the principles of the 'Triple Bottom Line of Sustainability' concept, namely to use Environmental, Social and Economic outcomes as a measure of performance and sustainability of the energy efficient upgrading process. There was a considerable reduction in energy consumption as a result of the upgrading. This is a positive from an environmental point of view. However, there is concern about the ability to meet the 2020 and 2050 targets without wide scale implementation of upgrading schemes. In reality, these upgrading interventions will also have to go deeper if the targets are to be achieved. A progressive approach would be to include the dwellings occupants in the upgrading process by providing information, training and support.

Socially the upgrading programme was also a success. The occupants generally reported that the upgrading had a positive influence on their lifestyles. They were particularly happy with the stoves and the replacement of the front and rear doors. Negatively, many complained about the additional vents and many had or intended to block them up. Many found that the new heating controls systems were too complex to use effectively and reverted to the one hour boost. Extra care needs to be taken during the upgrading process to explain the necessity and value of good quality ventilation and also the how to use the heating controls. This could lead to more healthy living environment and more energy savings could be made.

Though not the intention of the study a number occupants said that they had become more energy conscious. With targeted training and information the potential to improve energy saving could be greatly increased.

Economically, the process is less convincing. The study found that there was a considerable payback period and without large incentives there is a poor return on investment. It should be remembered that the LA availed of a competitive procurement process where large scale roll out potentially reduced the cost of upgrading individual dwellings. This might not be the case for an individual private homeowner.

9.1.4 Contribution to knowledge

There are an increasing number of investigations been carried out to achieve energy demand reduction, understand and change energy use behaviour in the domestic sector. However, the majority of these studies are limited in scale and unidisciplinary. This dynamic empirical research project, undertaken over a considerable timescale, represents the most recent detailed attempt undertaken to establish a real energy use and environmental characteristics attributable to housing in Ireland.

The contribution to knowledge comes in three forms:

- 1) The methodological design of this project, offers a unique contribution to research. The mixed mode evidence-based, multi-disciplinary approach, encompassing both qualitative and quantitative methods was used to establish and understand real energy usage and the effect of energy efficient upgrading of social housing in Ireland;
- 2) The research findings contribute to the body of knowledge in the area of actual domestic energy use, the effect of energy efficient upgrading and understanding domestic energy use behaviour. In particular the longitudinal study provided long term energy use monitoring data pre- and post- upgrading establishing the real effect of the upgrading. The occupant engagement offers a greater depth of understanding of occupant understanding and behaviour characteristics;
- 3) The study involved the original design, production and installation of a wireless, remote energy and environmental monitoring system. Though serious problems persisted gathering accurate data from the system the design provides a good basis from which a more robust system can be developed.

9.1.5 Future work

This research has shown that dwelling energy consumption encompasses a complex independence of many quasi-steady state and highly dynamic conditions. It has been highlighted through the document that research in this sector though gaining traction is relatively undeveloped. To make a substantial impact on reduction energy consumption in the domestic sector future research needs to espouse a transdisciplinary approach gaining knowledge of whole building energy usage and occupant behaviour, using monitoring and targeting and inductive qualitative methods. As a continuation of this research an action research approach will be adopted to educate occupants on energy saving techniques and evaluate the outcomes. The emphasis will be on an occupant participatory approach where knowledge about the barriers and enablers of reducing energy consumption will be gained through a collaborative process. The

results will be monitored over a considerable period to establish if deeper savings can be made and if these savings can be retained in the long term.

Improved techniques for gathering and returning user information needs to be developed to improve outcomes and future advance a user centred design process. Through a more sophisticated user characterisation, it can be argued that user centred design can offer a significant contribution to the field.

Further research is required to improved accuracy of simple predictive airtightness and energy models for Irish dwellings. The first step along this path is to undertake and formally collated wide scale airtightness testing. Airtightness testing should be encouraged for all envelope adaption to dwellings to maximise energy savings credits. To meet these target building energy performance models need to be improved to reduce the performance gap between predicted and real energy performance. Further calibration work needs to be done to improve the building energy models. To calibrate these models extended monitoring and targeting and monitoring and verifications studies need to be supported.

In line with the requirements of the Energy Performance of Building Directive energy efficiency improvements need to be cost optimal. This research showed that there is a long payback period for the works carried out. Innovative ways of delivering cost optimal savings need to be explored including advance procurement and deep whole house retrofit which will be required to meet the 2050 targets.

9.1.6 Final Conclusions

The overall conclusion from the findings is that the 'shallow' upgrading programme has a significant positive effect on reducing energy consumption. However, further savings must be achieved if Ireland is to achieve the 2050 CO₂ targets. In its current form the upgrading strategy had a considerable payback period arguably making the economic viability questionable.

The study revealed the complex nature of energy consumption confirming there is not a linear relationship between the technical upgrading and the actual reducing in energy use. The study showed that although the dwellings are relatively homogenous there was a large variability in energy consumption and usage patterns. The quantitative data could not explain the reason *why* there was such variability making the qualitative research an integral part of the research. This phase revealed that the occupant's lifestyle patterns, attitudes and lack of knowledge about energy efficiency had a major effect on their energy use.

To maximise the benefits of upgrading it is clear that there should be multiple liaison sessions with occupants before, during and after works to ensure they understand why a particular process was carried out, whether regulatory or voluntary, and how to correctly deal with any new systems or processes.

Overall occupants were pleased with the upgrading but in many cases emphasised the aesthetic improvements above impact on energy use and comfort. Though adequate ventilation is critical for a healthy building and occupants, the design ventilation strategy needs to be revisited as the passive wall vents were a major complaint of the occupants.

Both pre- and post- upgrading there was a large gap between the theoretical energy predicted by DEAP and the measured energy consumption. Energy prediction models need to improve to more accurately assess if energy and carbon targets are being achieved. One area in particular is the energy performance associated with the airtightness.

The design and implementation of a bespoke monitoring system is difficult. Since the start of the research there have been many technological advances in energy monitoring systems. However, most of these are for commercial application and often expensive. There is still no 'off the shelf system' to monitor domestic energy and environmental parameters required for future research. Care needs to be taken when commissioning such a system to ensure accuracy of data being delivered.

This research has been a long, sometimes difficult and frustrating, sometimes exhilarating and fulfilling journey. Over the six year period, the researcher has aimed to contribute to the body of knowledge on the effectiveness of energy upgrades in social housing and suggests improvements to upgrading practices which will help Ireland achieve carbon reduction targets as well as making homes more comfortable for occupants. This research has shown what is working well but also suggests the need for more research and has identified many gaps in knowledge and measurement techniques. The research therefore has identified a research pathway for the future as the quest will continue to further deepen our understanding of these important issues.

Policy makers may seek straightforward prediction models of how a particular policy will yield a particular result. However, this study has shown that such predictions are difficult to stand over. In reality, this and previous research has only scratched the surface of understanding how to accurately predict domestic energy consumption.

Appendices

2. Eligible Works

As outlined in Circulars N7/09 and SHIP 2010.20, the following works are eligible for energy efficiency funding:

- Pre and post works BER (Required);
- Attic Insulation to meet current building regulation standards;
- Wall insulation (cavity, external cladding, internal improvement, as appropriate);
- Replacement of boilers over 10 years old with condensing boilers to current standards and/or installation of space and water heating controls;
- Draught proofing measures;
- Replacement of windows and external doors in compliance with current regulations;
- Radon test and Installation of radon protection measures e.g. external sump;
- Consideration should also be given to the use of sustainable materials in delivering on the above improvements.

This is, however, not an exhaustive list and additional information and technical guidance on best practice for retrofitting is available as an appendix to Circular SHIP 2010.10. Authorities are also invited to consult with the Department's Adviser for further technical support and advice at any stage.

Authorities should note that the following works are not eligible for funding:

- Solid fuel central heating systems. However, authorities may continue to claim for solid fuel room heaters/stoves under the programme where fireplaces are being blocked up to improve energy efficiency; **It should be noted that where a Local Authority chooses to install both a solid fuel and an oil or gas system, in addition to the capital cost of the oil or gas system not being eligible for funding, the improvement in terms of kWh per m² per year resulting from the inclusion of oil or gas boiler in post works BER must be excluded from calculations on submitted payment claim forms.**
- Energy efficient light bulbs;
- Attic insulation or windows and door replacements that do not meet current building regulation standards;
- Boilers that do not meet current standards or where time and temperature controls were not installed.

Appendix B

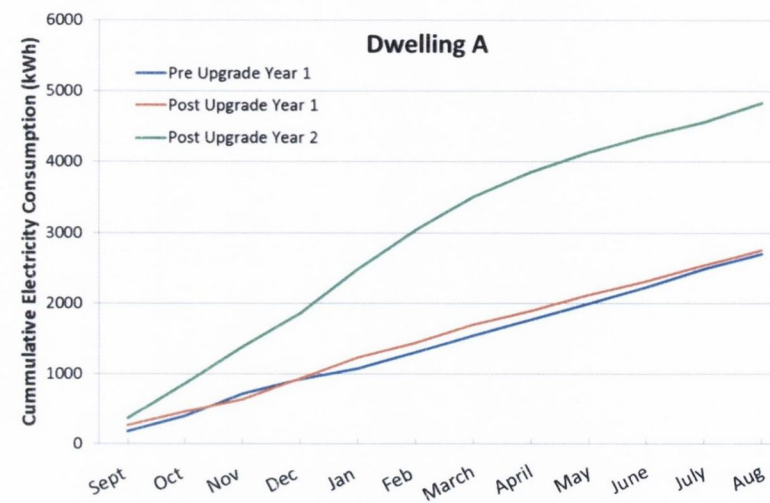
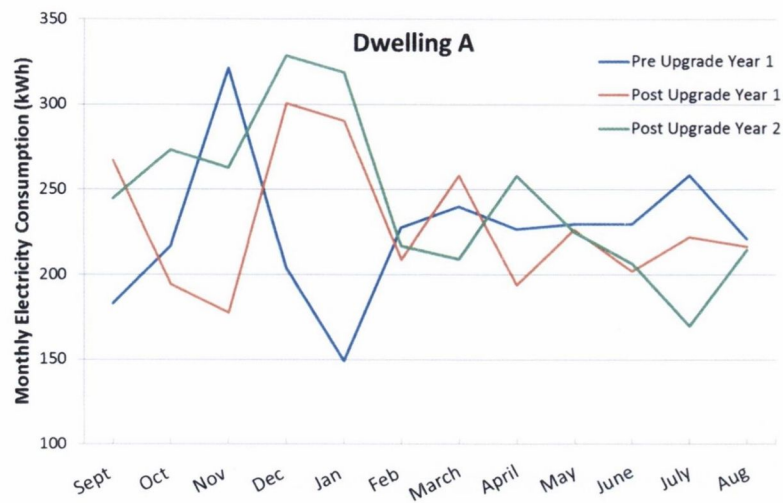
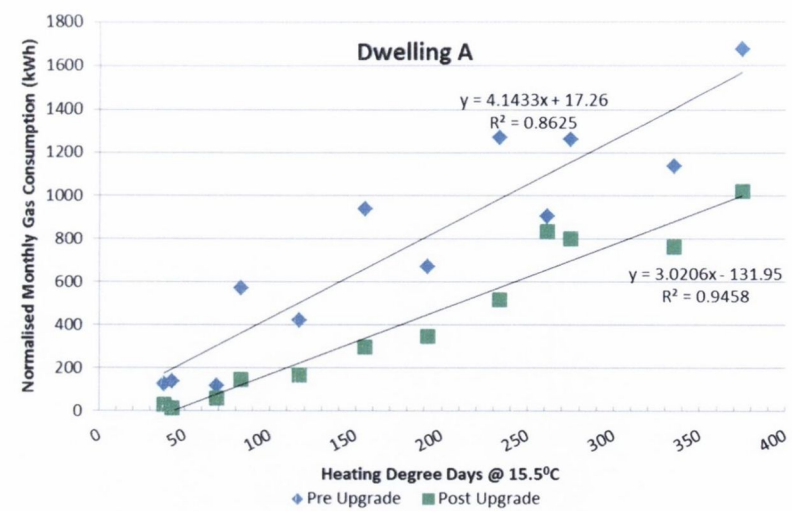
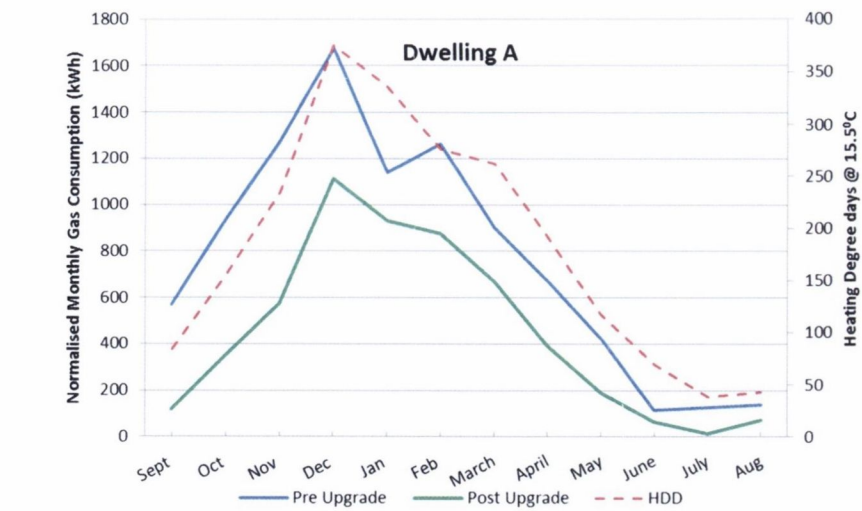


Figure 70 Dwelling A Normalised Gas Consumption and Linear regression, Monthly and Cumulative Electricity Consumption

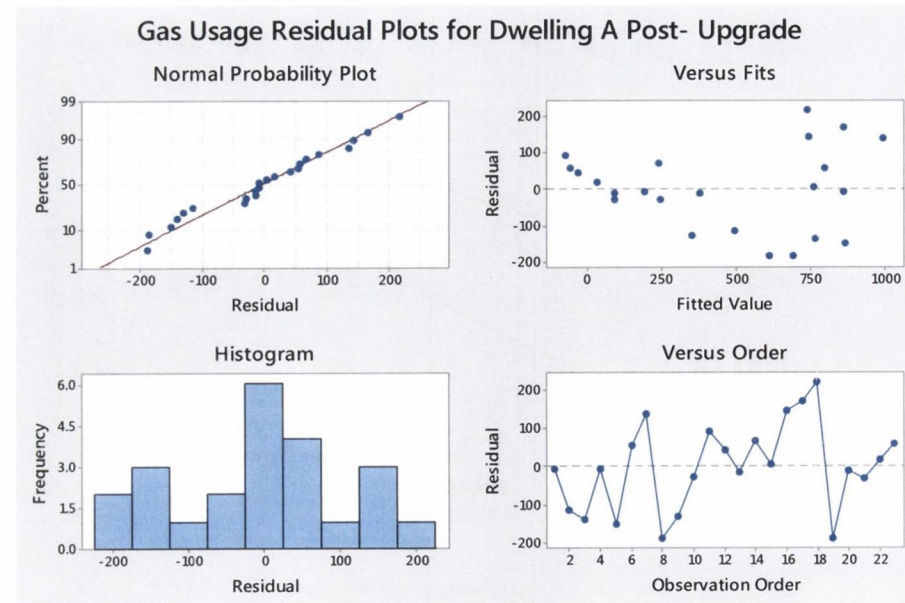
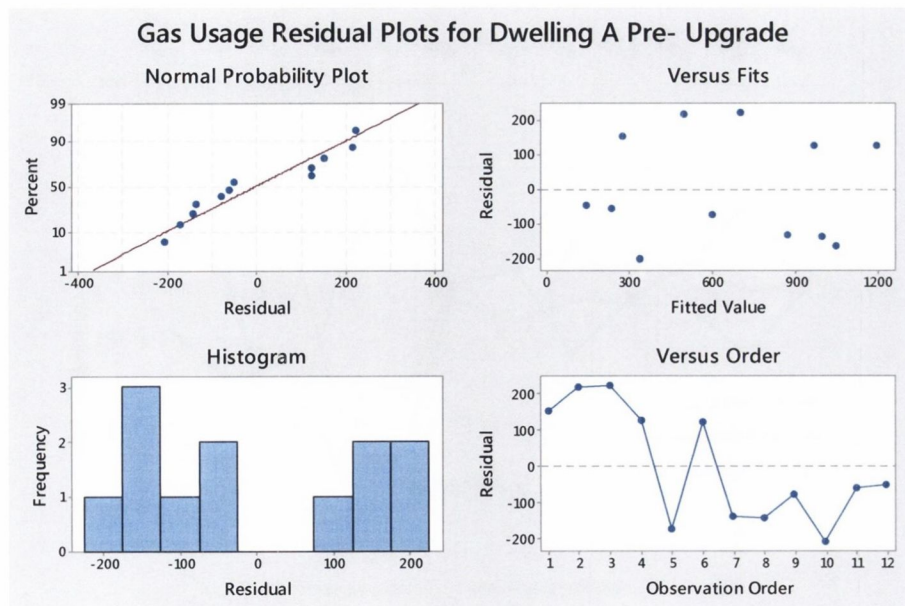


Figure 71 Dwelling A Pre- and Post- Upgrading Residuals Plots

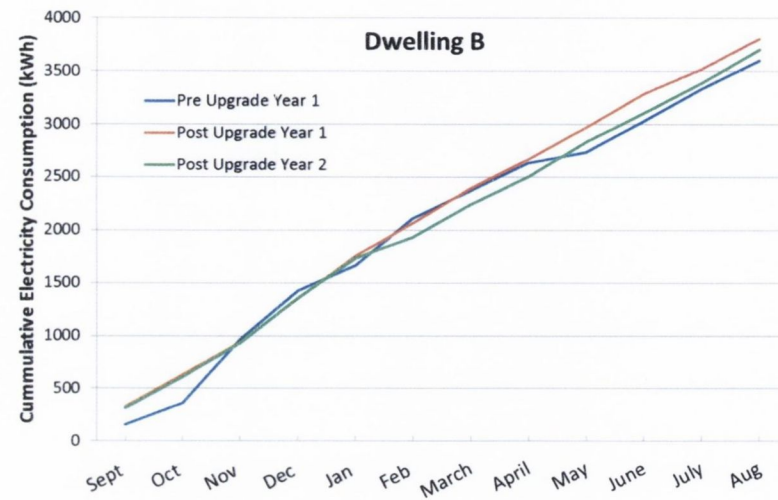
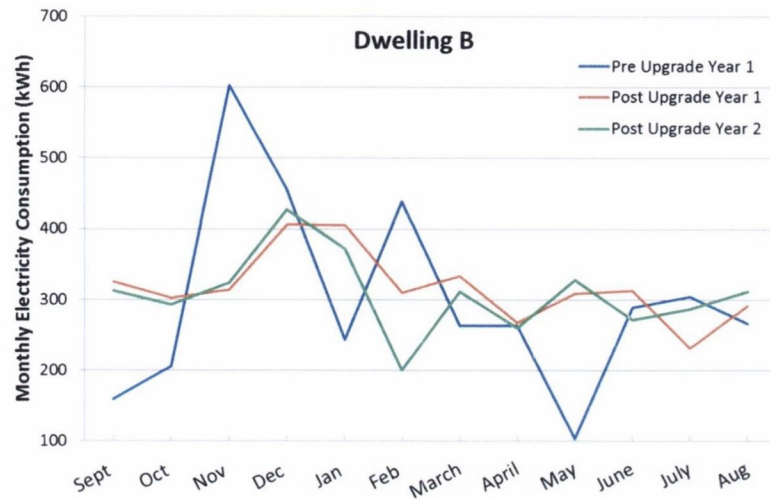
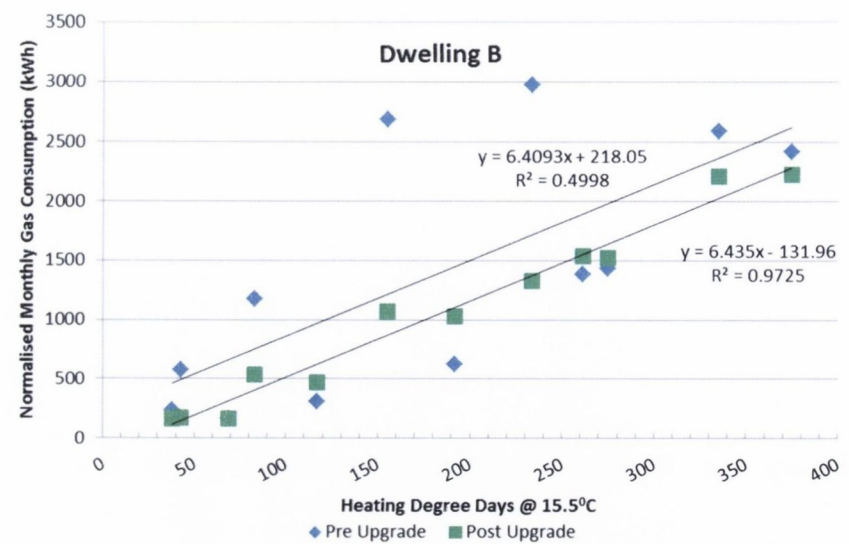
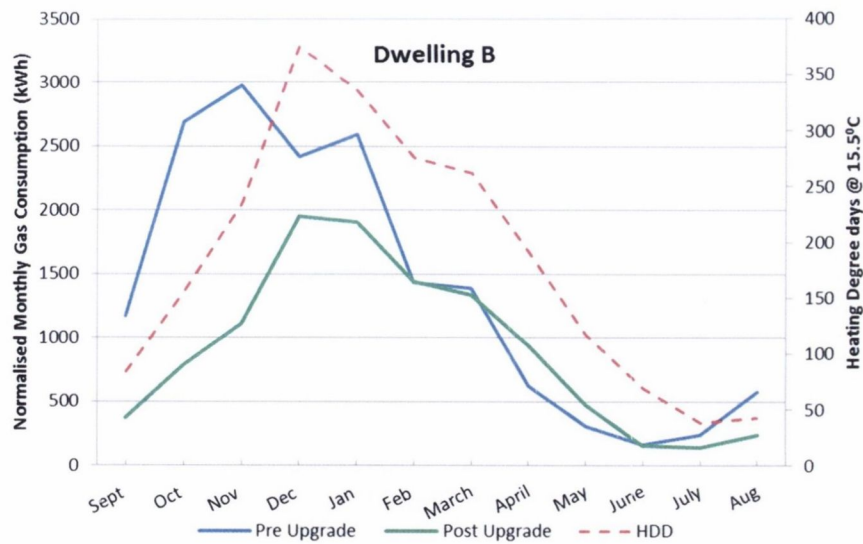


Figure 72 Dwelling B Normalised Gas Consumption and Linear regression, Monthly and Cumulative Electricity Consumption

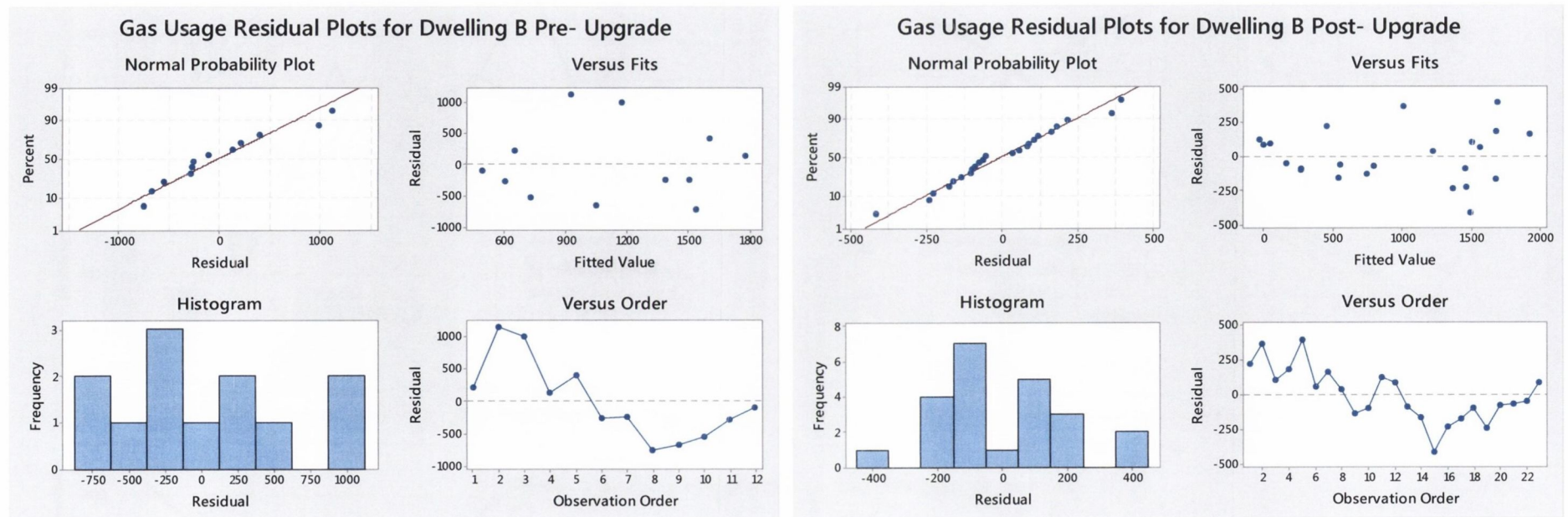


Figure 73 Dwelling B Pre- and Post- Upgrading Residuals Plots

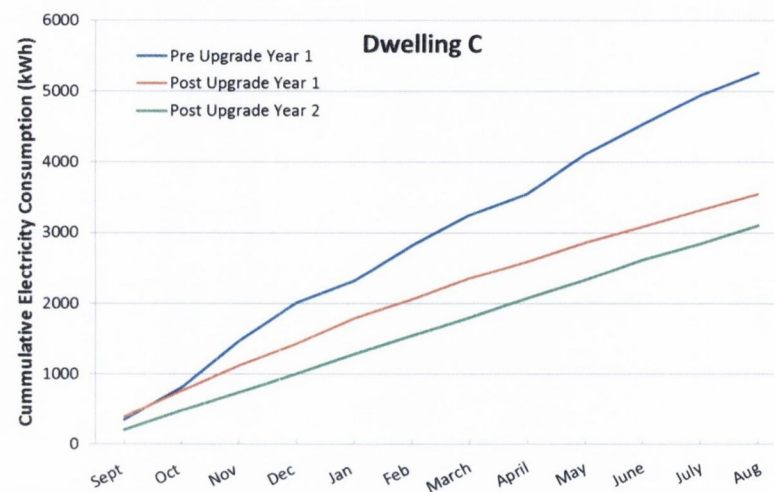
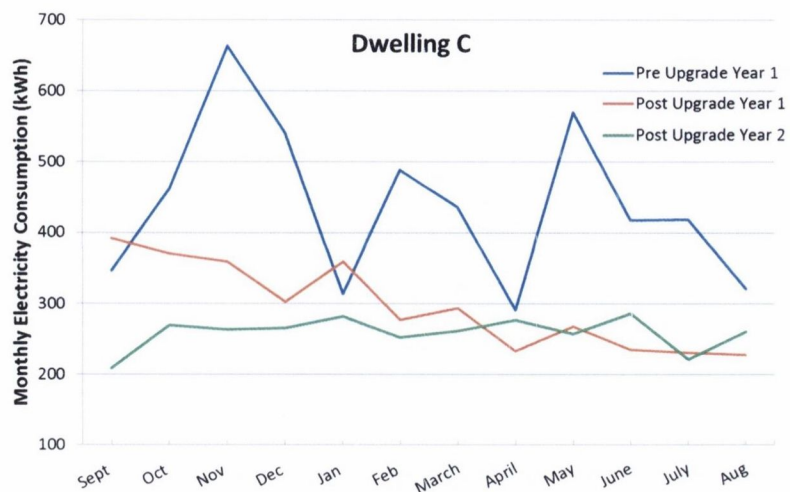
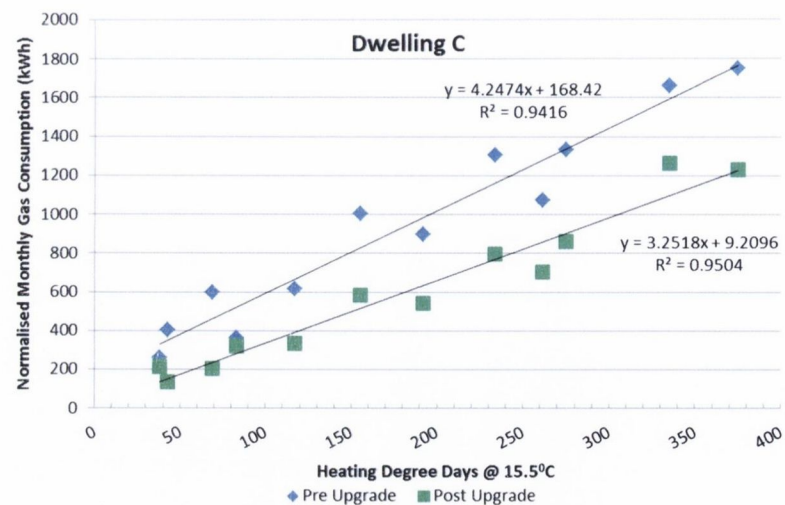
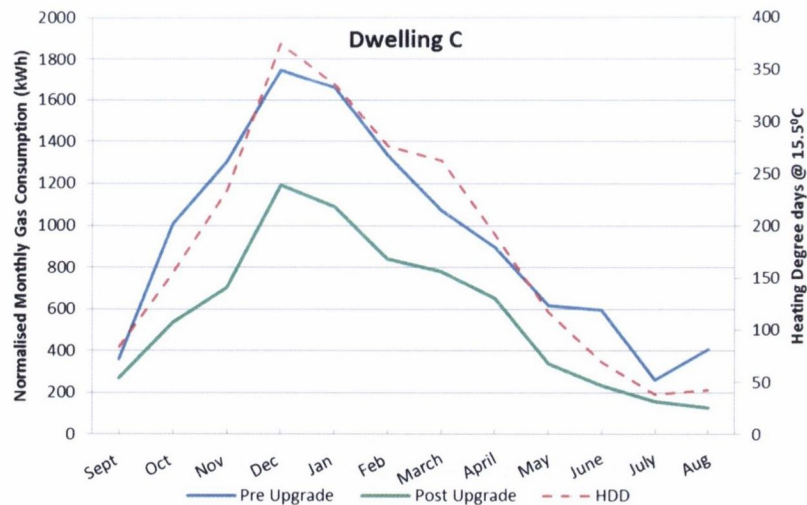


Figure 74 Dwelling C Normalised Gas Consumption and Linear regression, Monthly and Cumulative Electricity Consumption

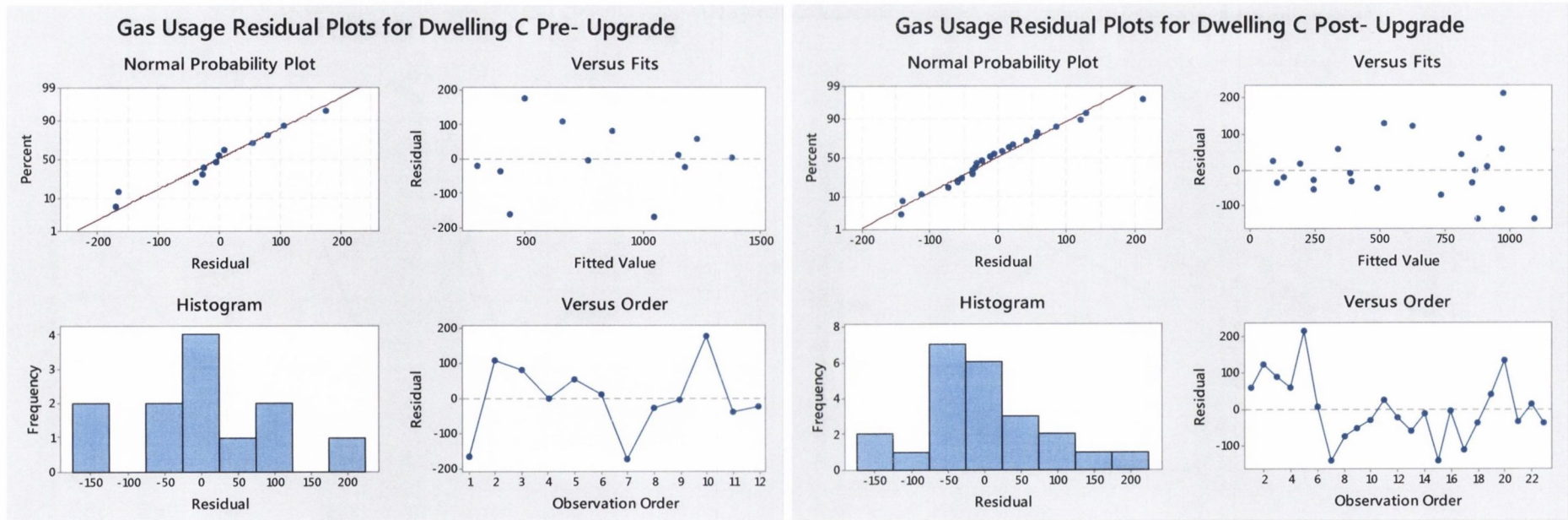


Figure 75 Dwelling C Pre- and Post- Upgrading Residuals Plots

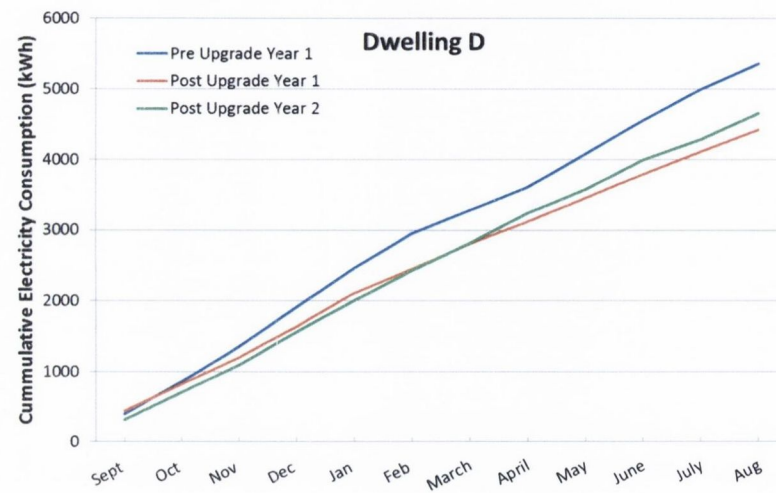
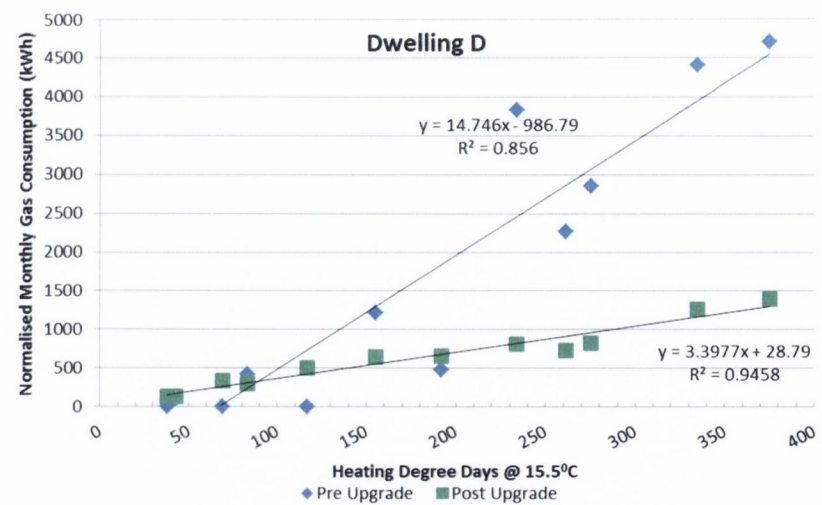
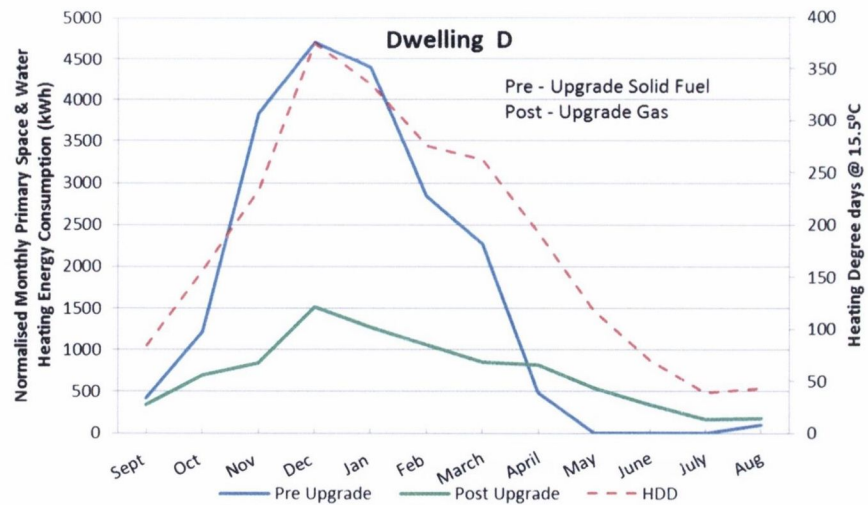


Figure 76 Dwelling D Normalised Gas Consumption and Linear regression, Monthly and Cumulative Electricity Consumption

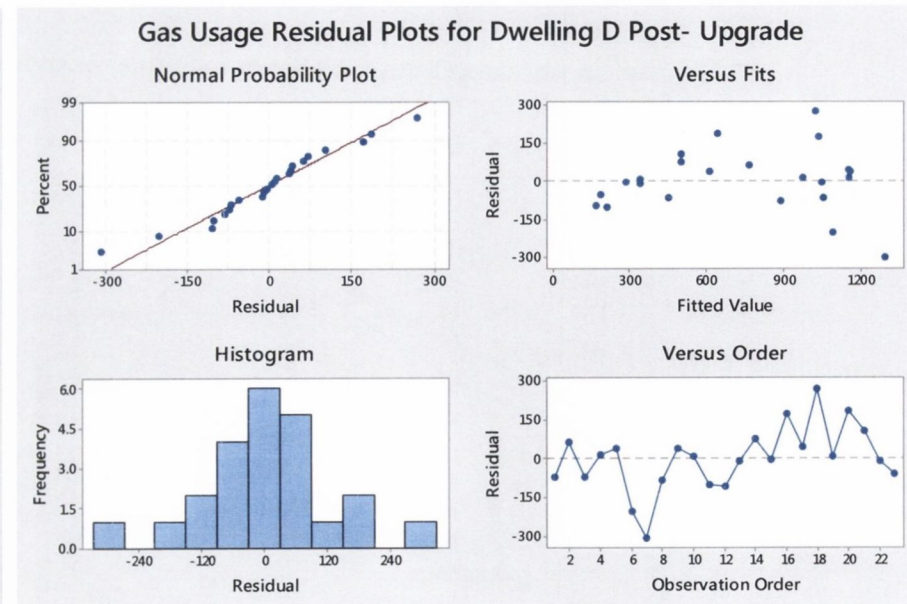
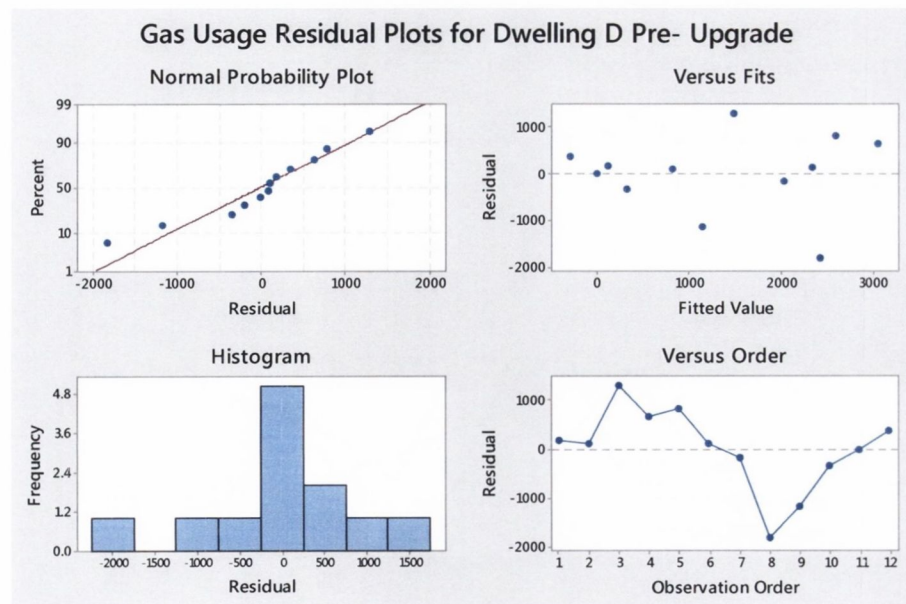


Figure 77 Dwelling D Pre- and Post- Upgrading Residuals Plots

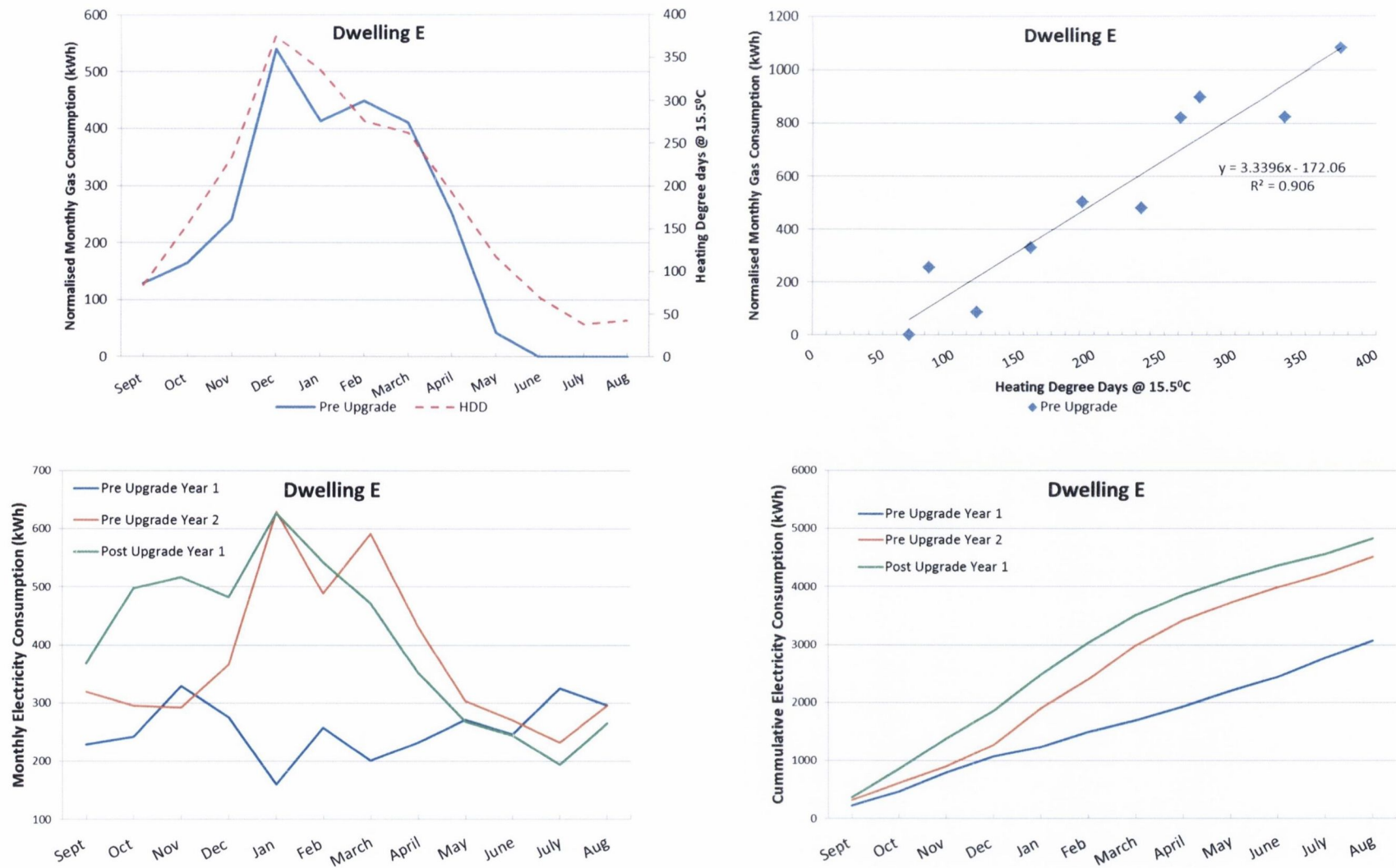


Figure 78 Dwelling E Normalised Gas Consumption and Linear regression, Monthly and Cumulative Electricity Consumption

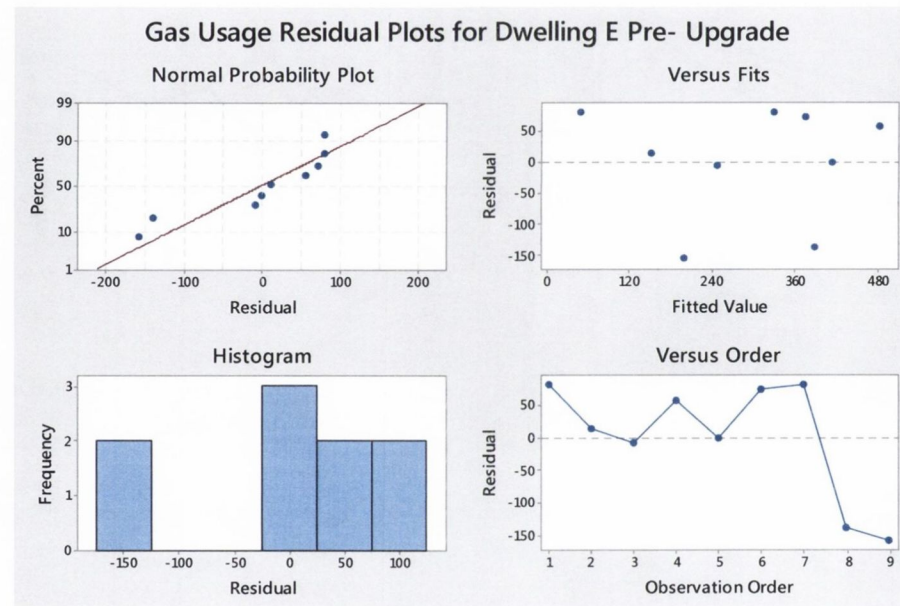


Figure 79 Dwelling E Pre- and Post- Upgrading Residuals Plots

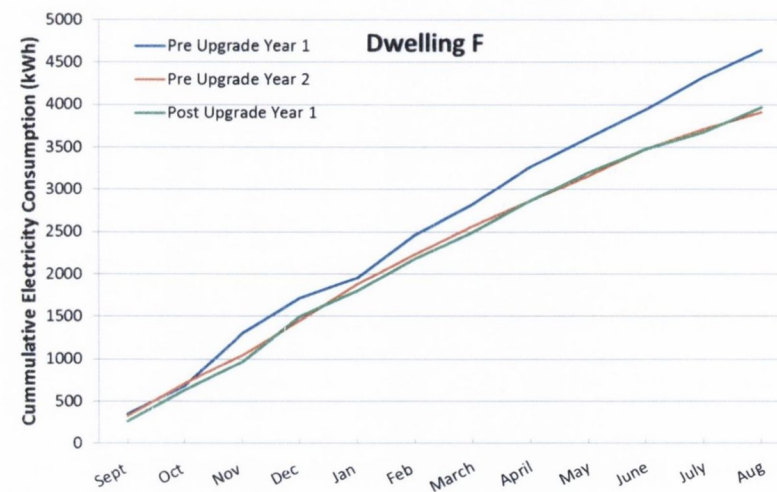
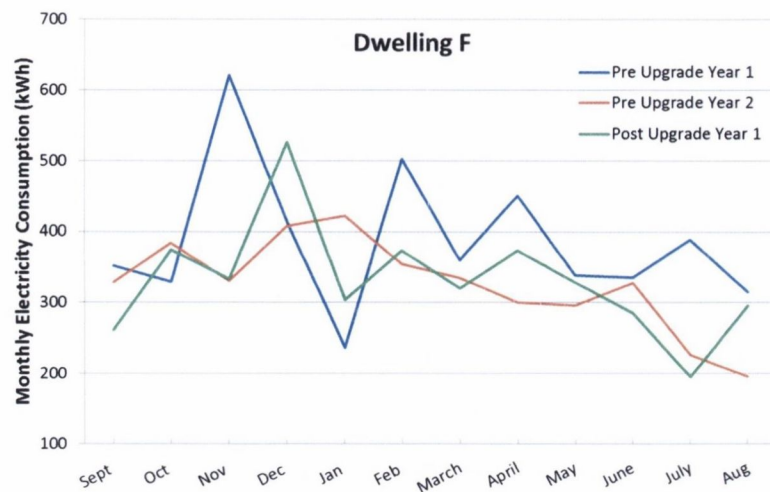
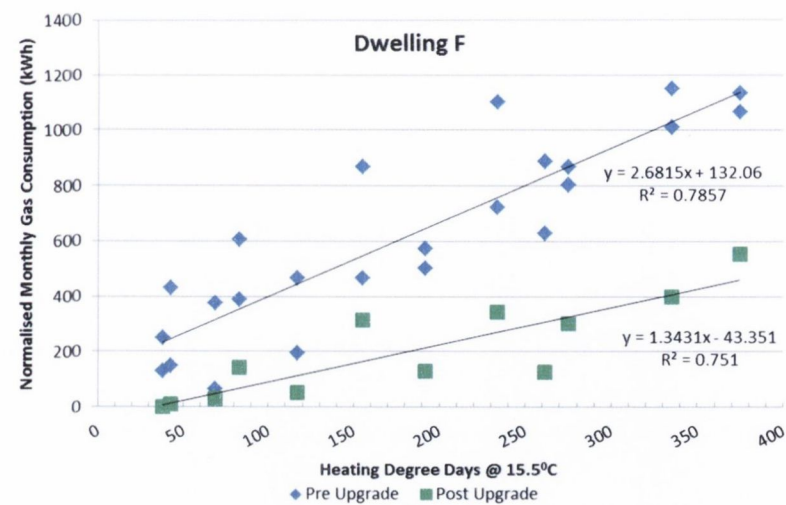
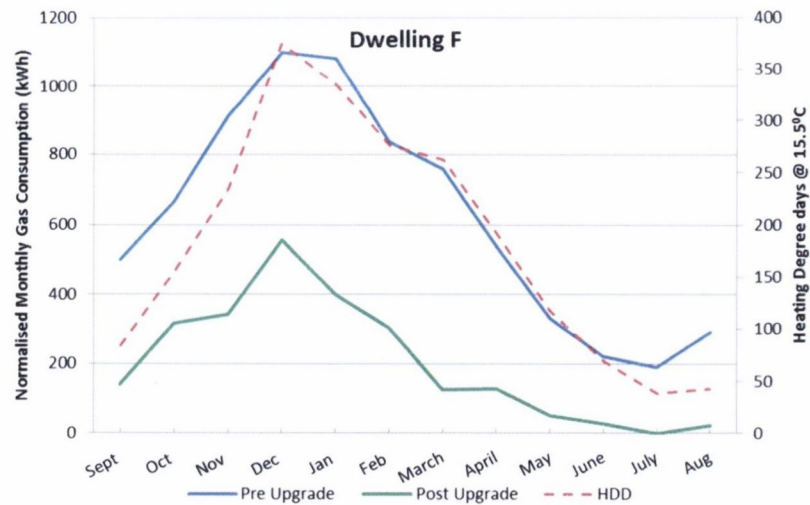


Figure 80 Dwelling F Normalised Gas Consumption and Linear regression, Monthly and Cumulative Electricity Consumption

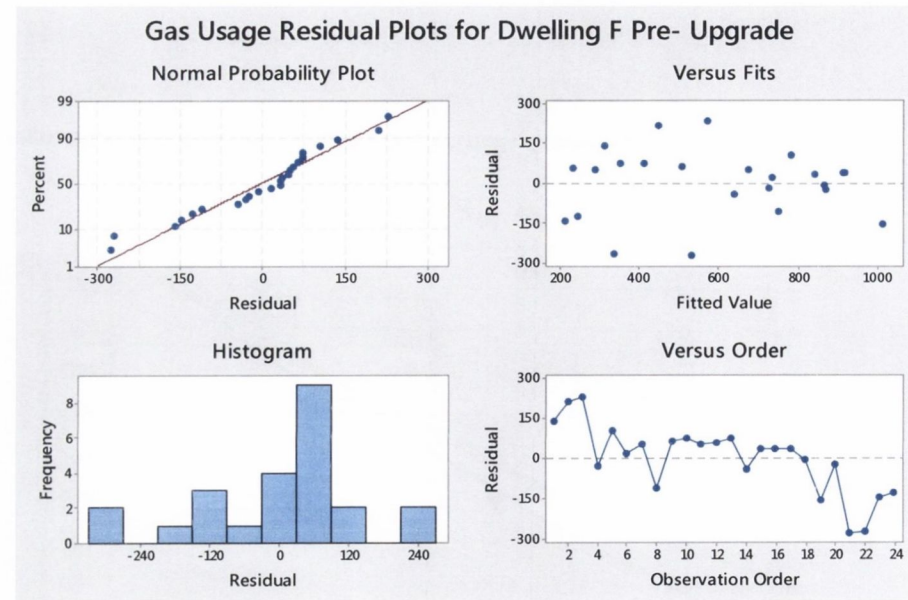
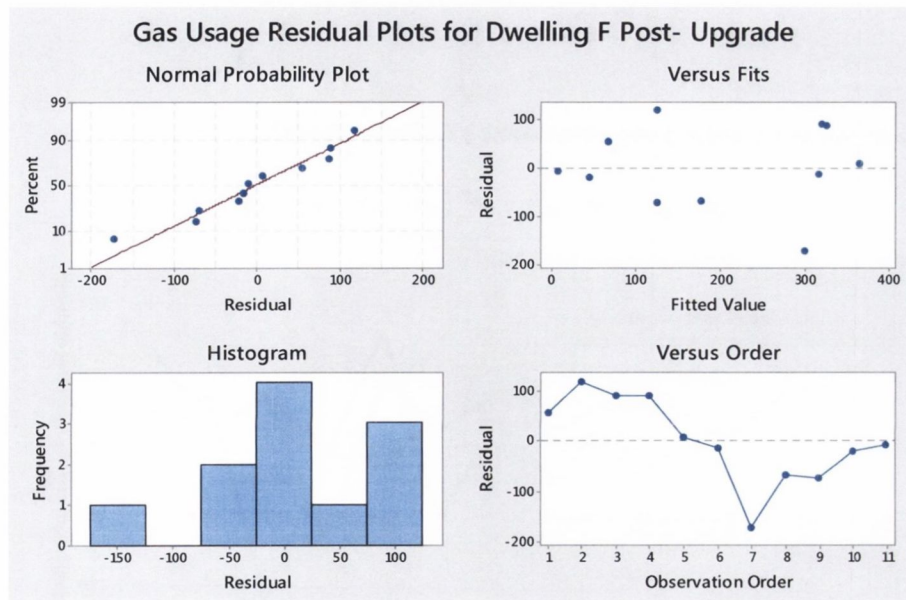


Figure 81 Dwelling F Pre- and Post- Upgrading Residuals Plots

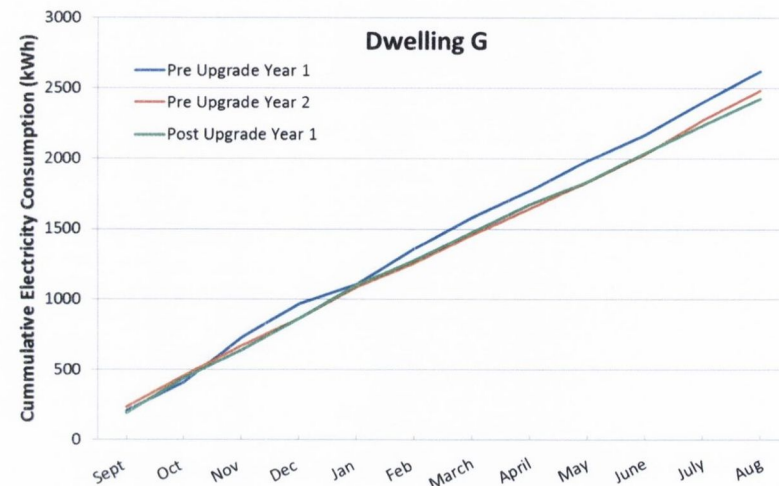
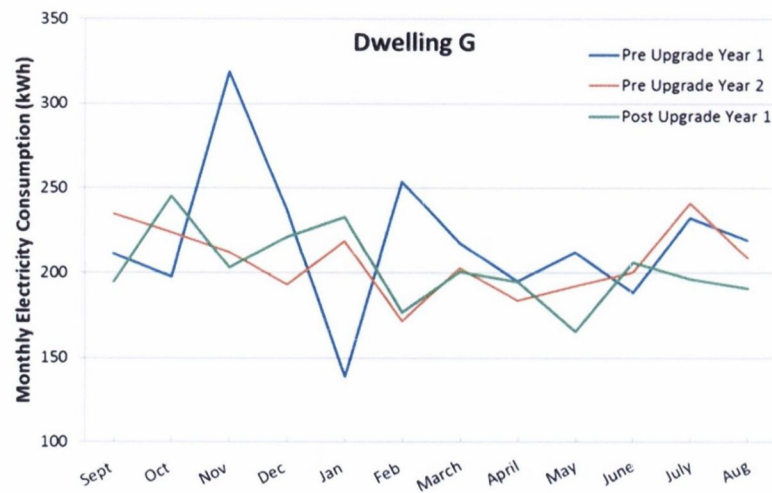
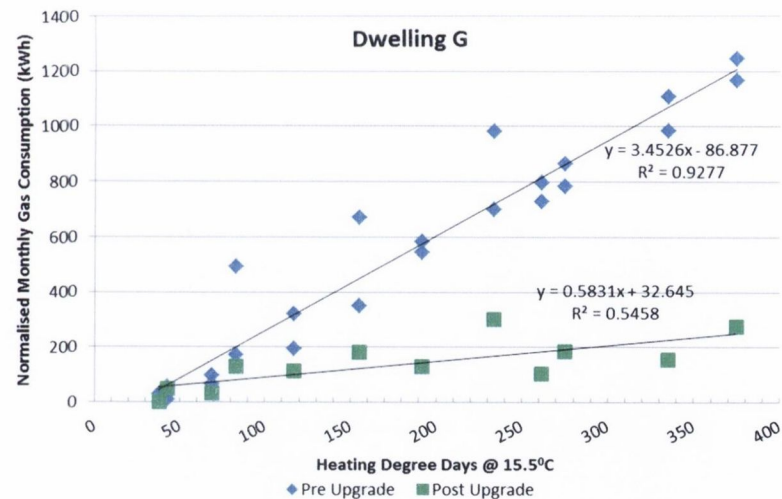
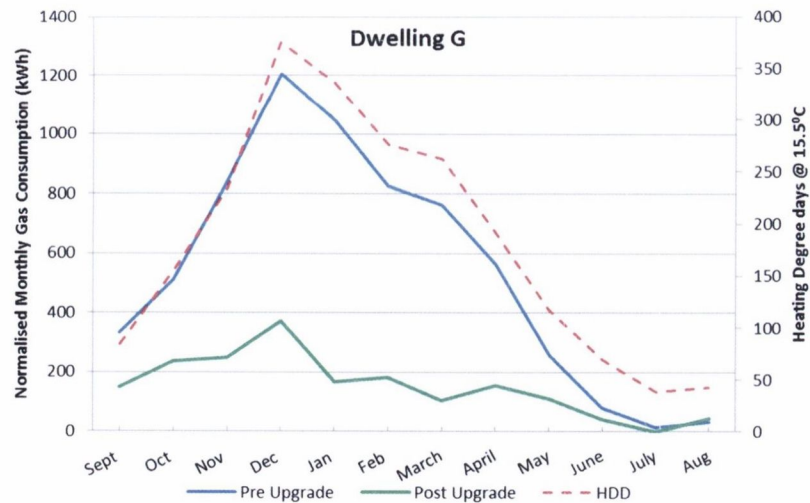


Figure 82 Dwelling G Normalised Gas Consumption and Linear regression, Monthly and Cumulative Electricity Consumption

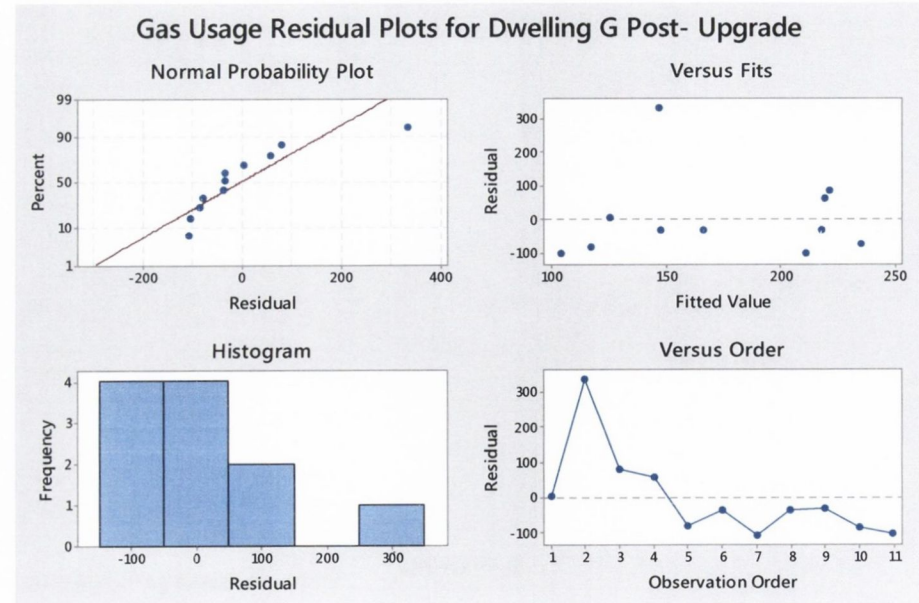
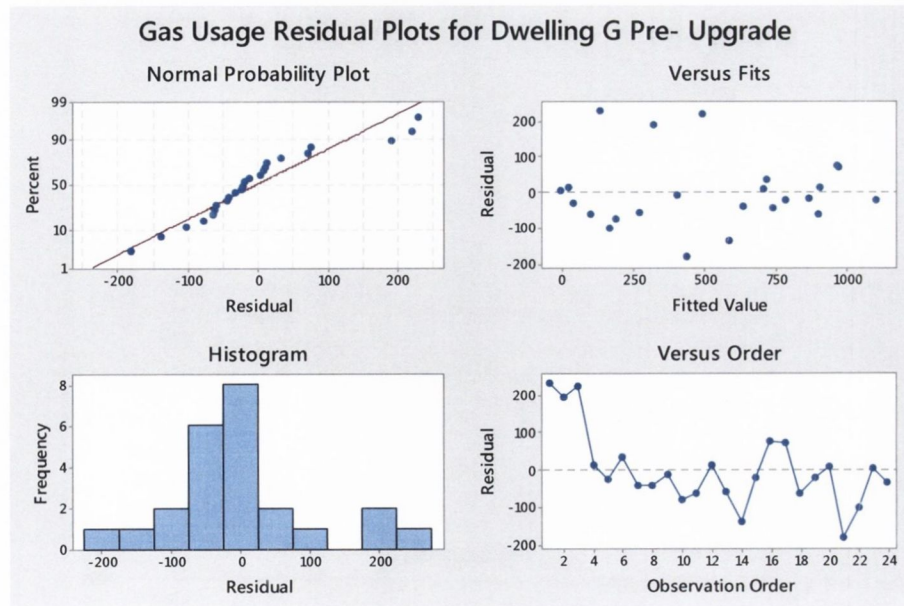


Figure 83 Dwelling G Pre- and Post- Upgrading Residuals Plots

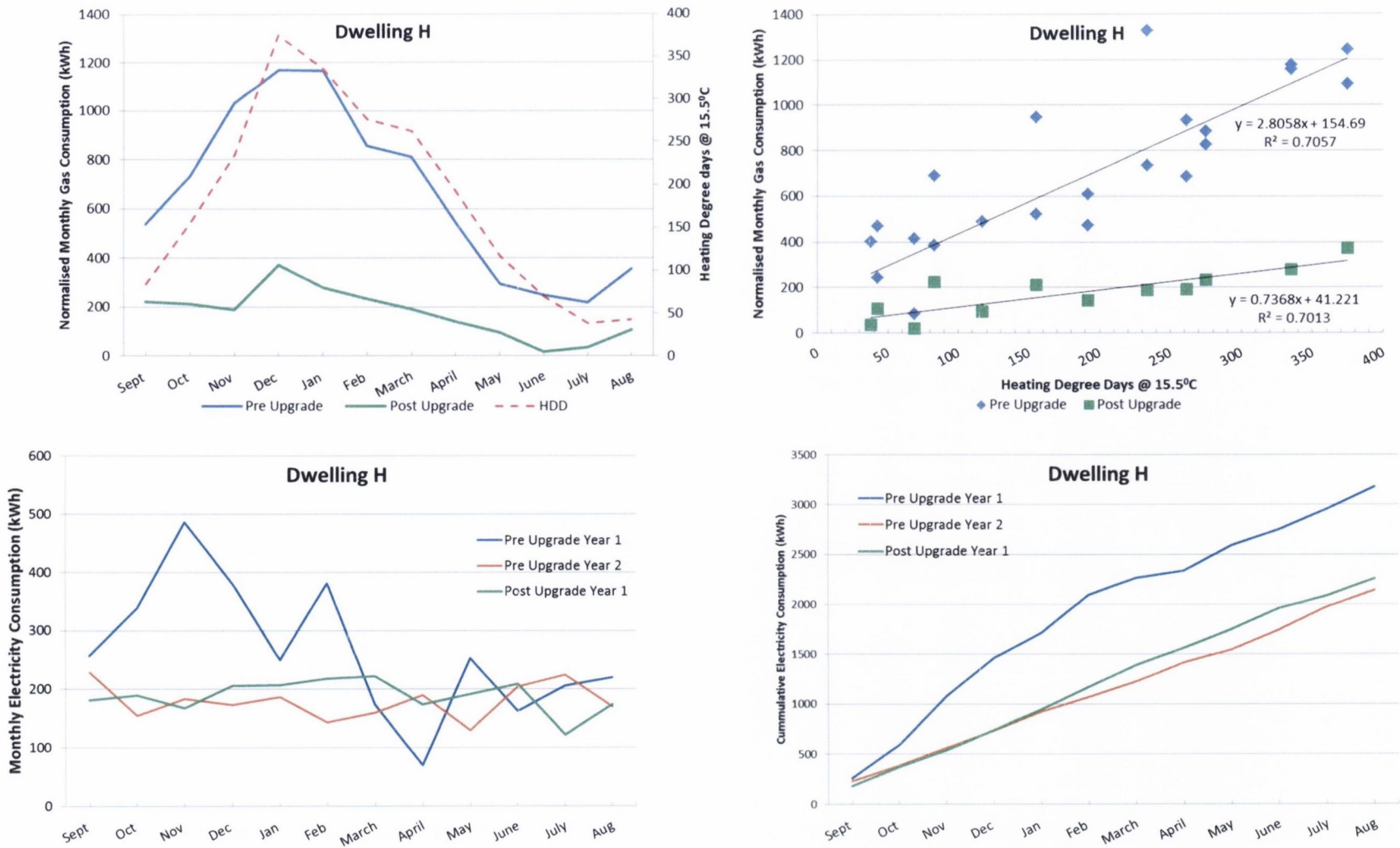


Figure 84 Dwelling H Normalised Gas Consumption and Linear regression, Monthly and Cumulative Electricity Consumption

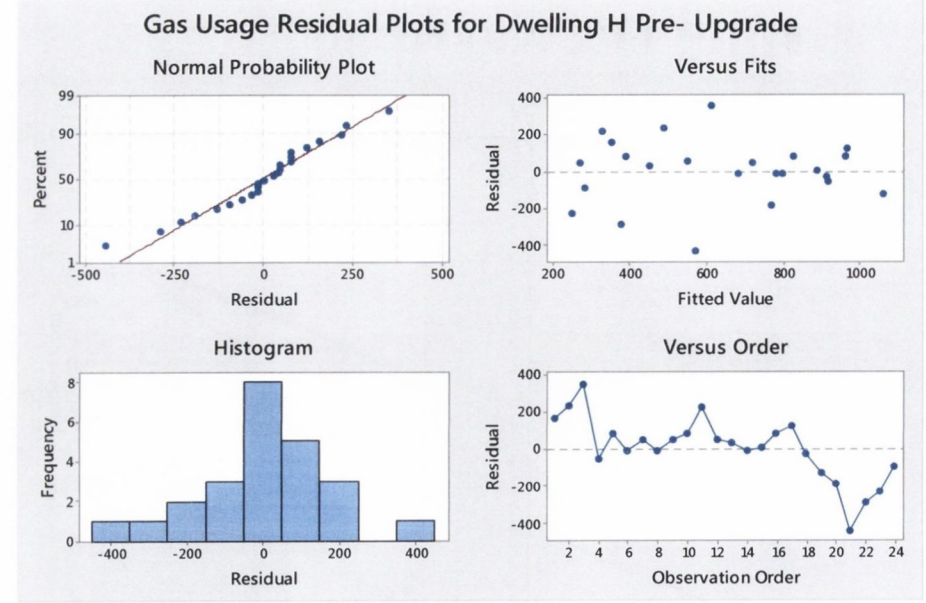
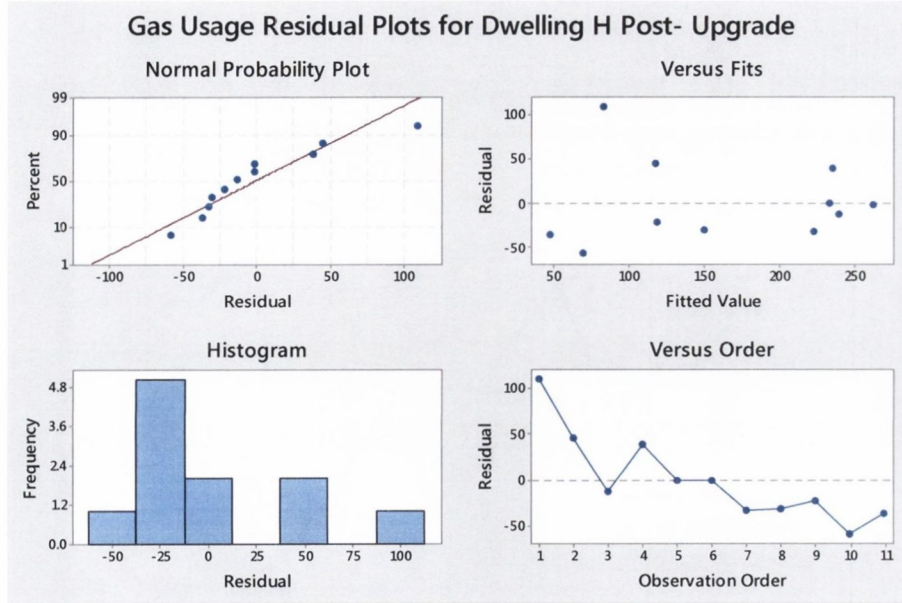


Figure 85 Dwelling H Pre- and Post- Upgrading Residuals Plots

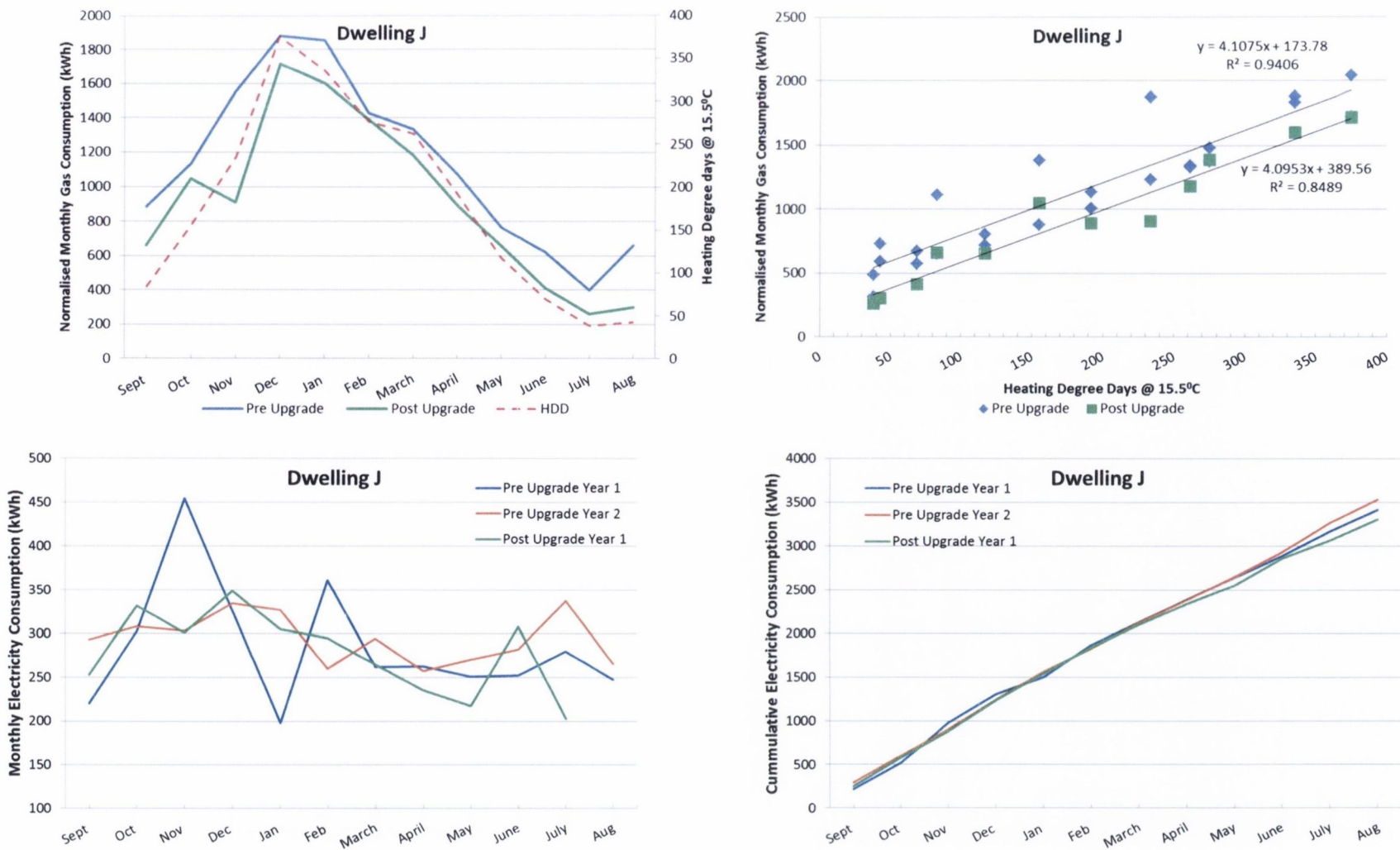


Figure 86 Dwelling J Normalised Gas Consumption and Linear regression, Monthly and Cumulative Electricity Consumption

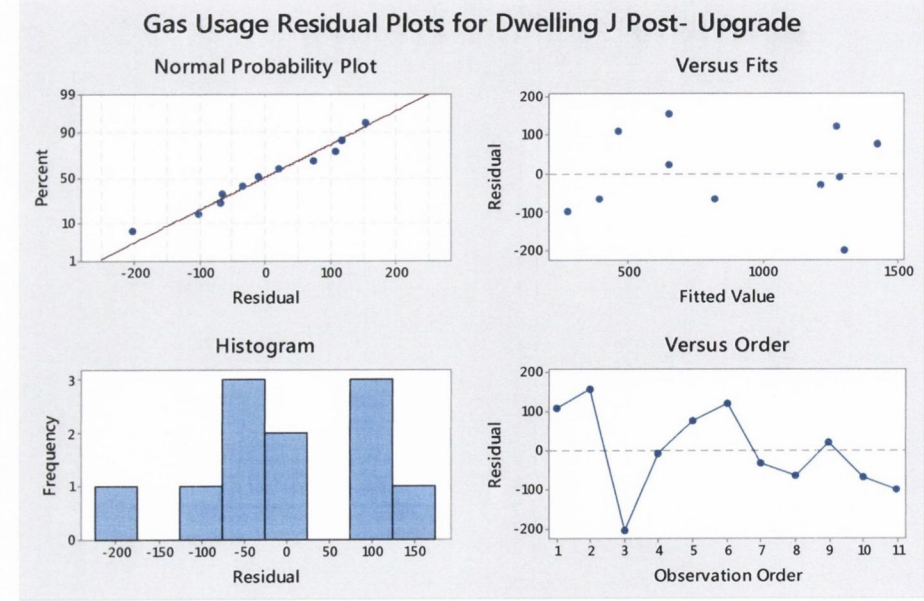
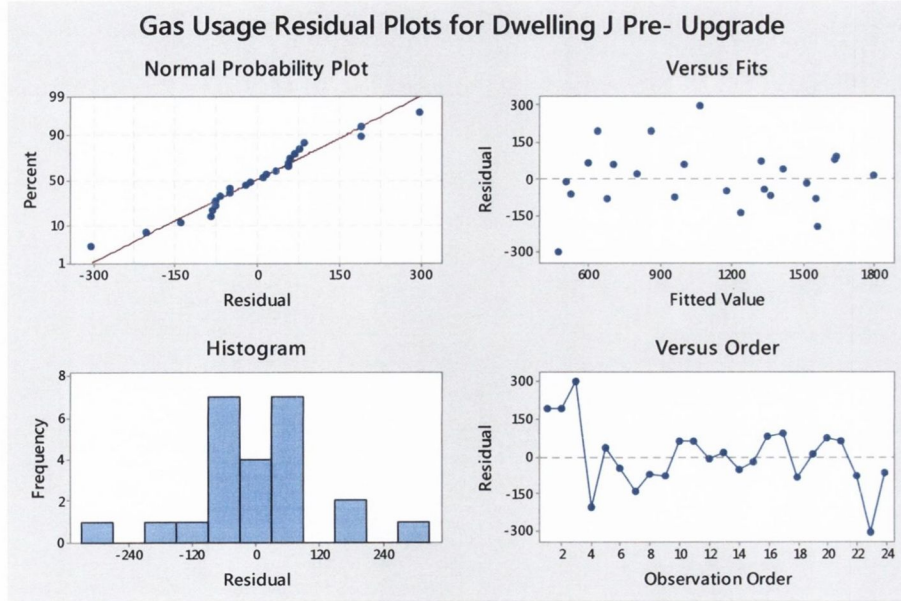


Figure 87 Dwelling J Pre- and Post- Upgrading Residuals Plots

Appendix C

Kilkenny Energy Monitoring Programme

Informed Consent Form – Consent for Participation in Research Interview

I volunteer to participate in the research project conducted by Derek Sinnott from Waterford Institute of Technology. I understand that the project is designed to gather information relating to energy use in social housing in Kilkenny. I will be one of nine households interviewed for this portion of the research.

- 1. My participation in this project is voluntary. I understand that I will not get paid for my participation.
- 2. I can withdraw from the interview at anytime and I am not compelled to answer any questions I do not feel comfortable answering.
- 3. I understand that the interview will last approximately 30 – 40 minutes. Notes will be written during the interview. A digital audio of the interview may be undertaken.
- 4. I understand that the researcher will not identify me by name or address in any reports using information obtained from this interview, and that my confidentiality as a participant in this study will remain secure. Subsequent uses of records and data will protect the anonymity of all individuals involved.
- 5. Specific details of the interview to Kilkenny County Council in any way to prejudice any existing relationship with the authority.
- 6. I have read and understand the explanation provided to me. I have had all my questions answered to my satisfaction and I voluntarily agree to participate in this study.
- 7. I have been given a copy of the consent form.

Participant (Block Capitals)

Participant (Signature)

Researcher (Block Capitals)

Researcher (Signature)

Appendix D

Energy Performance of Buildings – Interview Questionnaire

Please provide as much as possible of information required. The aim of the questionnaire is to help us better understand issues related to the energy performance of the buildings.

Pre- upgrading Interview

Name:	Date of Interview
Address:	Consent Form Signed Yes ☐ No ☐

Occupancy Characteristics

Number						
Adult 1	18 – 25	26 – 35	36 – 45	46 – 55	56 – 65	65+
M ☐ F ☐	☐	☐	☐	☐	☐	☐
Adult 2	18 – 25	26 – 35	36 – 45	46 – 55	56 – 65	65+
M ☐ F ☐	☐	☐	☐	☐	☐	☐
Children	Infant 0 – 5		5 – 11		11 – 17	
	1	2	3	1	2	3
	☐	☐	☐	☐	☐	☐

Occupancy rate (hours per day)

Income and Employment

Which of the following describes your employment status:	Adult 1	Adult 2	Dependant	Dependant	Dependant
Working full time (employed or self-employed)	☐	☐	☐	☐	☐
Working part time Hours	☐	☐	☐	☐	☐
Self Employed	☐	☐	☐	☐	☐
Working in the home	☐	☐	☐	☐	☐
Unemployed	☐	☐	☐	☐	☐
Retired	☐	☐	☐	☐	☐
Student	☐	☐	☐	☐	☐
Disabled / Dependant	☐	☐	☐	☐	☐
Other:	☐	☐	☐	☐	☐
Proximity to work (km)					

What is the combined gross household income?				
Annual	Under €10000	€10000 - €15000	€15000 - €20000	Over €20000
	☐	☐	☐	☐
Details if given:				

Post- upgrading Interview

Name:	Date of Interview
Address:	Consent Form Signed Yes ☐ No ☐

Occupancy Characteristics /Income and Employment

Q: Has there been any changes in occupancy characteristics, income or employment since the last interview

- If yes, elaborate

Standard of living

Q: How would you describe your overall standard of living

- Comfort, general environment, health

Q: Has the upgrading had an effect on your standard of living (positive or negative)

- If so, elaborate
- What are the main factors that affect your standard of living

Q: Is the condition of the house today typical of its day to day condition

Space and Water Heating

Q: What are your general space and water heating energy usage patterns

- Typical hours per day/week
- How have you adapted to the new system
- Do you think your usage is wasteful
- What is the primary driver of your usage

Q: Do you use your secondary space heating regularly (open fire)

- If so give usage details
- What fuel do you use and typically how much

Coal (no. of bags & size) _
Briquettes (no. of bales) _
Timber _
Other _

Q: Do you still use the kettle to heat water

- If yes, give details

Q: Do you still use immersion heating

- If yes, give usage details

Appliances

Q: Tell me about your typical appliance usage patterns e.g. Cooking, Televisions/Phones, Washing & Ironing, Buying appliances, Showers, Lights etc.....

Q: Do you believe that any of your appliance energy usage is wasteful

- If so elaborate

Q: Do you turn off appliances when you leave the room

- If Yes, Fully or standby
- If No, elaborate on reasons why

Bills

Q: Outline how you deal with your energy bills

- Planning, budgeting, paying etc.....

Upgrading

Q: Describe your overall experience of the upgrading process

- What did and didn't work for you
- What is the best and worst aspect of the final product

Q: Can you suggest anything to improve the process

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