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Towards Nearly Zero Energy Buildings:

The Interrelationships of Materials, People and Operational Energy Demand Practices for Residential Buildings in Ireland

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Contents

Declarations

This thesis or any part thereof, has not been, or is not currently being submitted for any degree at any other university.

Paul Moran

Paul Moran

The work reported herein is as a result of my own investigations, except where acknowledged.

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Paul Moran

Abstract

To combat the energy demand and global warming potential emissions of the building sector, the European Union has made mandatory the introduction of nearly zero energy buildings (nZEBs) in all its member states. Starting from the end of 2020, all new buildings or those receiving significant retrofit must show a very high energy performance standard with energy performance levels based on the cost-optimal framework methodology. Similarly, this is a requirement for all public buildings from the end of 2018. The population of Ireland is expected to increase by around one million people to almost 5.7 million people by 2040, requiring at least an additional half a million new homes. Additionally, 1.9 million housing units in Ireland are required to be retrofitted for the Irish national housing stock to be considered nZEB standard. Thus, work on approximately 2.5 million residential homes is required to achieve an Irish nZEB housing stock by 2040. Moreover, the role of people occupying buildings with regards to their energy usage behaviours, habits, perceptions and attitudes is central to ensuring buildings have a low environmental operational impact while maintaining healthy comfortable living conditions.

This research adopted an interdisciplinary methodological design that combined engineering and social sciences to investigate the environmental, economic and social impacts of residential buildings in Ireland moving towards nZEB standards by examining the interrelationships between the operational energy demand practices in buildings, the people occupying the buildings and the materials and technology used in the construction/retrofit of the buildings. The environmental, economic and social impacts of semi-detached and terraced houses were examined considering (i) past and present building regulations, (ii) the materials and technology employed in the buildings, (iii) future electricity generation fuel mix, (iv) future energy pricing, (v) discounting operational energy costs, (vi) the space heating, domestic water heating and appliance energy demand practices of people occupying the buildings and (vi) people's attitudes, perceptions and social norms regarding energy consumption and the environment.

The research found that minimising the environmental and economic impact of the materials and technology used in the construction of new build nZEB residential buildings is becoming equally, if not more, important than the environmental and economic impact from people's operation of residential buildings**.** Assuming 10% of the 0.5 million required new residential units are semi-detached buildings complying with passive house thermal fabric and ventilation standards to achieve nZEB energy performance standards, they will potentially save an estimated 116.3 TJ/m^2, 0.8 kilotons CO_{2eq}/m^2 and €2.6 million/m^2 over 60 years compared to 2011 Irish building energy performance standards.

For semi-detached gas heated houses constructed between 1991 and 2002 in Ireland and retrofitted to new build nZEB energy performance standards, the operation of the building has a greater life cycle energy and life cycle GWP impact compared to the materials and technology invested from the retrofit. Despite issues with both approaches, reducing the energy consumption of households was found to be more effective by investing in materials and technology rather than attempting to get householders to change their energy demand practices. For a monitored social housing estate in Ireland which underwent an energy efficiency retrofit, the average gas and electricity energy cost savings the year following the energy efficiency retrofit were €141 and €140, respectively, despite energy savings not meeting their theoretical potential. The householders were found to play a key role in the success (or lack thereof) of the retrofitting efforts to reduce the energy consumption of the residential buildings.

All in all, retrofitting Irish semi-detached gas heated houses constructed between 1991 and 2002 with the aid of government grants to new build A2 nZEB energy performance standards has the potential to achieve savings for householders ranging from €254,000/m^2 to €331,000/m^2, 3006 tCO_2/m^2 to 3554 tCO_2/m^2 and 46,135 GJ/m^2 to 50,196 GJ/m^2 over 30 years. However, for these type of environmental and economic savings for new build and existing buildings in Ireland to be realised, significant investment is needed in energy demand research in the Irish built environment to be able to fully understand how the interrelationships between building materials and technology, people occupying the buildings and operational energy demand practices in buildings drive building energy consumption and energy savings.

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List of Publications

The work contained in this thesis consists of the following publications in international peer-reviewed journals:

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Chapter 3: Moran, P., Goggins, J. & Hajdukiewicz, M., "Super-insulate or use renewable technology? Life cycle cost, energy and global warming potential analysis of nearly zero energy buildings (NZEB) in a temperate oceanic climate," *Energy and Buildings*, vol. 139, pp. 590–607, 2017.

Chapter 4: Moran, P., O'Connell, J., & Goggins, J., "Sustainable energy efficiency retrofits as buildings move towards nearly zero energy building (NZEB) standards," *Energy and Buildings*, vol. 211, pp. 109816, 2020

Chapter 5: Rau, H., Moran, P., Manton, R. & Goggins, J., "Changing energy cultures? Household energy use before and after a building energy efficiency retrofit," *Sustainable Cities and Society*, vol. 54, pp. 101983, 2020

Chapter 6: Moran, P., Manton, R., Rau, H., Hajdukiewicz, M., & Goggins, J., "How Effective is an Energy Efficiency Building Retrofit and Feedback on Energy Usage for Reducing Energy Consumption in Irish Social Housing?," *(in preparation)*

Chapter 1. Introduction

1.1 Environmental Impact of People and Buildings

With the world's energy consumption and population increasing, climate change is linked to humankind's heavy reliance on fossil fuels to meet energy demand and the resultant production of greenhouse gases (GHGs) [1]. The Intergovernmental Panel on Climate Change (IPCC) report strong evidence that suggests the increase in GHGs in the atmosphere is changing the world's climate [1]–[4]. Climate change is predicted to have a negative effect on the world unless proper mitigation measures are implemented [1]–[4]. Various international agreements have been made to help address climate change including the United Nations Framework Convention on Climate Change Treaty [5], the Kyoto Protocol [6] and the Paris Agreement [7]. The Paris Agreement is the latest of these agreements and contains a pledge from 195 countries to hold global temperatures to a maximum rise of 1.5ºC above pre-industrial levels [7]. The European Union (EU) has also set ambitious carbon reduction and energy efficiency targets for 2020 [8] and 2030 [9] to help achieve its long-term 2050 target of 80% GHG emissions below 1990 levels [10].

Despite the goals set by various governments and organisations for sustainable development, current global energy supply demand shows that these goals are not being met [11]. Global energy demand increased in 2017 with 72% of the rise met by fossil fuels, a quarter by renewable energy and the remainder by nuclear power [11]. Global energy-related CO_2 emissions reached historic levels in 2017 which oppose the reductions required to meet the Paris Agreement climate change goals [11]. Fossil fuels, such as oil, coal and natural gas, are the world's main source of energy [12], accounting for 81% of the world's energy sources in 2016 [12]. The combustion of fossil fuels to supply the world's energy is a major source of CO_2 emissions. 32,316 Mt of CO_2 were produced from the combustion of coal, peat, oil, oil shale and natural gas in 2016 with coal/peat/oil shale accounting for 44.1% of the emissions, oil producing 34.8% and natural gas producing 20.4% [12].

In 2010, buildings accounted for 32% of total global final energy demand, 19% of energy related GHG emissions and approximately one third of black carbon emissions [1]. CO_2 emissions from the building sector have continued to rise by nearly 1% per year since 2010 [13]. Improvements in energy efficiency are being offset by increasing population and building floor areas [13]. Furthermore, only a third of world countries have mandatory codes for their respective building sector [13]. It has been estimated that energy demand may double or even triple due to an increase in housing in developing countries, population growth, urban migration, household size and increasing levels of wealth and lifestyle [1]. Energy efficiency policies to mitigate the environmental impacts of buildings have been categorised as new building constructions, building retrofits, efficiency of building equipment and the energy consumption behaviour of building occupants [14]. Building standards, financing, incentives and information to householders are viewed as measures to tackle the environmental impacts of new building constructions, building retrofits, efficiency of building equipment and the energy consumption behaviour of building occupants [14].

1.2 EU and Irish Building Energy Performance Policy

The European Union (EU) has focused on reducing the impact of buildings on the natural environment through several directives and roadmaps for its member states [8], [10], [15], [16]. The introduction of these policies may be among the factors as to why the EU has experienced a reduction in energy demand since 2010 [17]. Research in the UK suggests that energy prices may also have been a factor [18].

To combat their energy demand and GHG production, buildings in the EU are now being designed and constructed to tighter building standards and codes. The Energy Performance Building Directive (EPBD) introduced a new revised directive in 2013 [16] requiring the mandatory introduction of nearly zero energy buildings (nZEBs) in all member states. An nZEB is a building with a very high energy performance. The nearly zero or very low amount of energy required by an nZEB should be produced, to a very significant extent, from renewable sources, including those on-site or nearby. Starting from the end of 2020, all new buildings or those receiving significant retrofit must show a very high energy performance [16]. Similarly, this is a requirement for all public buildings from the end of 2018 [16].

The new nZEB building regulations in the Republic of Ireland (referred to as Ireland) require newly built residential buildings to achieve an energy performance coefficient (EPC) of less than 0.30 and a carbon performance coefficient (CPC) of less than 0.35 [19]. The new nZEB energy performance building regulations represent the 8th iteration of building energy efficiency standards in Ireland. Previous building energy efficiency standards were published in Ireland in 1991, 1994, 1997, 2002, 2005, 2008 and 2011 [20]. Draft Irish building regulations were also introduced in 1976 and 1981 [20].

The new Irish energy performance building regulations for residential buildings will represent the 4th iteration of building energy efficiency standards in Ireland since the introduction of Energy Performance Certificates (ENPCs). A standard assessment procedure for producing the ENPC of new and existing buildings in Ireland (and all EU member states) was introduced into legislation by the Energy Performance Building Directive (EPBD) [15]. ENPCs are seen as a tool for providing clear and reliable information to homeowners and tenants to compare and assess the energy performance of buildings [21], encourage owners to invest in improving the energy efficiency of the building through the provision of cost effective retrofit measures [21] and assist governments in developing policies to achieve national energy reduction targets in the building sector [22].

The energy performance assessment procedure generally includes an analysis of the (i) building form, (ii) thermal, solar and daylight properties of the building envelope, (iii) air permeability, (iv) space, water heating and ventilation systems, (v) fixed lighting systems and (vi) fuel and renewable energy sources. The energy demand is assessed under standard occupancy and climatic conditions of the respective country [22]. In Ireland, the ENPC is based on the energy demand for the heating season. The heating season in Ireland begins in October and finishes in May. The Irish standard assessment procedure is referred to as the dwelling energy assessment procedure (DEAP). It produces ENPCs known in Ireland as Building Energy Rating (BER) labels.

The minimum energy performance standards for residential buildings in Ireland have improved from the 2005 Regulations [23] to the 2011 Regulations [24] by 60% in terms of primary energy usage, as determined using DEAP [25] (Table 1.1). The primary energy consumption in a building of A1 and G ratings are 25 kWh/m^2/yr (i.e. 90 MJ/m^2/yr) and 450 kWh/m^2/yr (i.e. 1620 MJ/m^2/yr), respectively. Thus, the primary energy consumption of an A1-rated building is approximately 5% of that of a G-rated building.

Table 1.1: Timeline showing requirements of new dwellings built to Irish energy performance building regulations and conforming BER grades.

Timeline		Building Regulations			
		2005	2008	2011	2019
PART L (Dwellings)	% Improvement	Baseline	40% and renewable	60%	nZEB
DEAP	Primary Energy (MJ/m^2/yr)	540	324	216	162
	Carbon Emissions (kgCO$_2$/m^2/yr)	30	18	12	10
EPBD	BER Label	B3	B1	A3	A2

With nearly 90% of the existing EU building stock built before 1990 and a low rate of new to existing buildings (about 1% a year), retrofitting the existing building stock is necessary to meet EU's 2020 and 2030 energy efficiency targets [26]. It is estimated that over 97% of the EU building stock must be upgraded to achieve the 2050 decarbonisation vision [27].

Any major energy efficiency retrofit works will require buildings in the EU to achieve an nZEB minimum energy performance standard. In Ireland, major retrofit works are classified as energy efficiency retrofit works where more than 25 % of the surface area of the building envelope undergoes renovation [28]. To be considered an nZEB retrofit in Ireland, a residential building must achieve a minimum energy performance of 125 kWh/m^2/yr [28]. However, if an energy performance of 125 kWh/m^2/yr is found to be cost-optimally unfeasible, a cost-optimal retrofit solution, that does not achieve an energy performance of 125 kwh/m^2/yr, may be used instead [28]. An energy performance of 125 kWh/m^2/yr achieves a B2 BER.

1.3 Life Cycle Analysis in Building Design

Achieving more energy efficient buildings comes at an additional cost. In many instances, the design solutions involve additional material in constructing the building. Buildings and construction in the EU accounts for 50% of all extracted materials, 30% of water consumption and 33% of total generated waste [29]. Tighter building standards and codes are resulting in lower energy demand during a building's operation. However, this only represents one stage of a building's life cycle energy demand. Building life cycle analysis (LCA) assesses the impact of building production, construction, use and end of life during the building's life span. This is to ensure any strategy used to reduce the impact of the operational phase of a building does not offset the impact of a different stage of the building's life. As defined in EN 15978 [30], a building's life cycle is made up of its product stage, construction process stage, use stage and end of life stage.

The reduction of operational energy demand during the use stage due to stricter energy performance standards often requires an investment of materials into a building [31]–[33]. A previous review of embodied energy in residential buildings found the embodied energy share in a building's life cycle energy for conventional buildings to range from 5% to 36%, low energy and passive house standard buildings to range from 11% to 57% and nZEB buildings to range from 69% to 100% [33]. Thus, the impact of the product, construction and end of life stage of a building's life cycle are becoming more significant as buildings become more energy efficient [31]–[38]. Some studies have started incorporating the impact of materials used into their zero energy building (ZEB) and nZEB definitions [38]–[40].

Because of the importance of selecting sustainable materials and the use of LCA in building design, France, the Netherlands and Finland have committed for LCA to be mandatory in building design [41]. Germany and Austria have introduced semi-mandatory requirements for building LCA. Several commercial building sustainability assessment schemes (BREEAM and LEED) and residential building sustainability assessment schemes (Irish Green Building Council's Home Performance Index) have included the embodied impact of construction materials in their performance criteria. The EU recently published guidelines on sustainability indictors for office and residential buildings that include using LCA [42]. In general, policy in the Irish construction sector fails to tackle the growing environmental life cycle significance of building material production processes.

1.4 The Role of People in Building Energy Use

While many EU governments have limited their inclusion of LCA in building design standards, many have directed considerable attention and resources towards retrofitting programmes aimed at improving the energy efficiency of residential buildings through technical means. In Ireland for example from 2000 to 2016, 375,000 Irish homes received government grants to retrofit their homes to a higher energy efficiency standard [43] through schemes such as Home Energy Saving, Better Energy Warmer Homes, Housing Aid for Older People, Greener Homes, Better Energy Homes, Better Energy Communities and Better Energy Area Based Grant Programme [44].

While useful in many respects, limitations exist with regard to the savings that can be achieved by upgrading buildings, with studies reporting average energy saving deficits to range from 14% to 98% [45], [46], [55], [47]–[54]. Scheer et al. found a shortfall in energy savings ranging from 28-44% for homes involved in the Better Energy Homes scheme [45], which provides grants to Irish homeowners for energy efficiency retrofits.

Limitations in energy savings can relate to observable short-term and long-term variations in household energy use that are attributable to the dynamics of everyday life [56], [57]. These complement (and perhaps even supersede in importance) ‘classical’ socio-economic factors such as household size and composition [58]–[61], household income [58]–[60], [62], [63], and tenure type [58], [60], [61], [64].

For example, a post-occupancy evaluation of the actual energy performance of 11 new low-energy dwellings in the UK revealed that 51%, 37% and 11% of the variance in heat, electricity and water consumption, respectively, between dwellings related to variations in householders’ everyday activities and habits [56]. Similarly, a systematic comparison of heating-related energy demand of five identical residential buildings in Denmark showed large variances arising from differences in how occupants used these buildings [57]. Evidence also exists of post-retrofit increases in energy use which (partly) cancelled out gains made through retrofitting [65]. These so-called rebound and 'backfire' effects can vary in both manner and scale [66]–[70], which suggested that post-retrofit changes in occupants' habits and related aspects of energy use deserved much greater attention than has hitherto been the case.

To help mitigate intensive energy consumption by building occupants and achieve energy and climate change targets, an Energy Efficiency Directive (EED) introduced in 2012 requires that energy consumers in EU member states receive feedback on their energy demand [71]. This involves providing energy consumers with smart metering, in addition to accessing additional consumption information where feasible and when financially cost effective. Furthermore, energy consumers with non-smart meters are to be provided with frequent billing information. The aim of providing energy consumers with energy demand feedback is for consumers to alter and develop more efficient energy demand behaviours.

1.5 Motivation and Aims

The population of Ireland is expected to increase (by around one million people) to almost 5.7 million people by 2040, requiring at least an additional half a million new homes [72]. Furthermore, there are currently 2 million housing units (detached houses, semi-detached houses, terraced houses and apartment units) built within Ireland [73]. 800,059 have received a BER label, with 730,641 currently not achieving cost optimal energy efficiency standard of 125 kWh/m^2/yr [74]. Assuming the remaining housing with no BER label were built before the mandatory BER labelling of new buildings in the 2000s, 1.9 million housing units in Ireland are required to be retrofitted for the Irish national housing stock to be considered nZEB standard. Work on approximately 2.5 million residential homes is required to achieve an nZEB residential building stock by 2040.

To determine building energy performance requirements for nZEBs, EU countries had to use a cost-optimal methodology framework to assess cost-optimal levels of minimum energy performance requirements for buildings/building elements/building materials [75]. The cost-optimal methodology framework assesses the global costs (or life cycle costs) for buildings/building elements/building materials and their respective impact on primary operational energy demand for space heating, cooling, ventilation, domestic hot water and lighting systems. This methodology [75] has been used to determine the cost optimal energy performance levels for Irish residential nZEBs [76]. Directives for achieving newly built and retrofitted nZEBs are important mitigation measures for achieving long term Irish energy demand and GHG emission reduction targets [77]. However, upon establishment of nZEBs in the residential market, increased attention should be placed on the environmental impact of building materials. For an nZEB design to be sustainable, it is necessary to assess its environmental and economic impact throughout its life cycle.

Moreover, the role of people occupying these buildings with regards to their energy usage behaviours, habits, perceptions and attitudes in how they operate buildings is central to ensuring buildings have low environmental operational impact while maintaining healthy comfortable living conditions. Many government-initiated retrofit programmes, including Ireland's, have a technocentric energy efficiency measure approach while behavioural changes are generally neglected [44], [78]. This is despite the gaps in performance of energy efficiency retrofit materials and technology in reducing building energy demand being partly attributed to the practices of people occupying buildings and the benefits they prioritise over energy savings. To be able to reduce the energy consumption effectively through energy efficiency retrofits, it is essential to study the interrelationships between the occupants, building systems, and behavioural aspects [79]. These interrelationships can be examined using a mixed method approach which combines both qualitative and quantitative data [80].

Thus, there exist a number of approaches to designing and evaluating the design of a residential new build and retrofit. This research aims to investigate environmental, economic and social impacts of residential buildings in Ireland moving towards nZEB standards by examining the interrelationships between the operational energy demand practices in buildings, the people occupying the buildings and the materials and technology used in the construction/retrofit of the buildings (Figure 1.1). The interrelationships between the operational energy demand practices in buildings, the people occupying the buildings and the materials and technology used in the construction/retrofit of the buildings are examined through the lens of the cost-optimal methodology framework, life cycle analysis and a mixed method approach. Overall, this research is adopting an interdisciplinary methodological design that combines engineering and social sciences with the objectives of:

- Using life cycle analysis to assess what impact the changes in the materials and technologies in residential building construction practices in Ireland is having on a building's environmental and economic impact as buildings move towards nZEB standards.
- Using and comparing the cost-optimal framework and life cycle analysis to examine effective building envelope materials and heating system technologies for designing and evaluating newly built and retrofitted nZEBs in Ireland considering their environmental, economic and social impact.
- Using a mixed method approach to explore how the interrelationships between building materials and technologies, operational energy demand practices in buildings and people occupying the buildings influence a building's environmental, economic and social impact following an energy efficiency retrofit and energy consumption feedback.

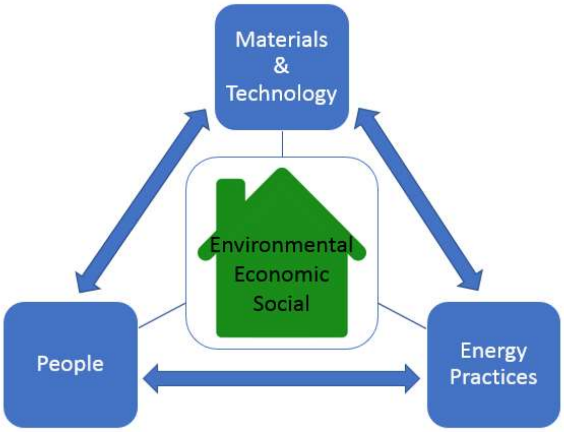


Figure 1.1: Flowchart of research which aims to investigate the environmental, economic and social impacts of residential buildings in Ireland moving towards nZEB standards by examining the interrelationships between the operational energy demand practices in buildings, the people occupying buildings and the materials and technology used in the construction/retrofit of the buildings.

1.6 Thesis Overview

Chapter 1 of the thesis introduces the research, outlining background, motivations and aims of the research. **Chapter 2** examines (i) past studies on the life cycle analysis of new build and retrofit residential buildings to gain a perspective on typical building material and operational energy demand environmental impacts and how other studies have approached their life cycle analysis, (ii) the effectiveness of material and technology focused building energy efficiency retrofits in reducing energy consumption and to identify reasons for their (in)effectiveness in reducing energy consumption, (iii) how social sciences can aid in understanding how and why the interrelationships between building materials and technologies, operational energy demand practices in buildings and people occupying the buildings influence a building's energy consumption and identifying reasons for (in)effective retrofits and (iv) the effectiveness of energy consumption feedback in reducing the energy consumption of people in buildings.

Chapter 3 examines from an Irish context how past and present building regulations for new buildings are impacting the building's materials and technology and occupant's operational energy use from an environmental and economic perspective using life cycle analysis. The effectiveness of the cost-optimal methodology for designing new residential buildings is explored and the direction that new building design strategies should take as Ireland moves to a decarbonised economy by 2050.

Chapter 4 investigates retrofit packages for improving the building material thermal efficiency and energy demand of gas-heated semi-detached and terraced houses in Ireland through the lens of the cost-optimal methodology framework and life cycle analysis. Using both theoretical and monitored case study buildings, the analysis examines whether a retrofit design and evaluation should be based on the cost-optimal methodology or a method that encompasses multiple life cycle environmental, economic and social indicators.

To help understand the building operational energy use and energy savings of people living in Irish co-operative social housing units, **Chapter 5** makes use of the concept of 'energy cultures' from social-scientific research on the cultural dimensions of domestic energy use. This chapter deploys the heuristic of energy cultures to investigate the interrelationships between (i) energy efficiency retrofitting, (ii) domestic energy use, (iii) material conditions, and (iv) social and cultural norms of householders and how each of these elements are impacted from a technocentric focused building energy efficiency retrofit.

Chapter 6 presents the findings from an energy consumption feedback study carried out on a group of households living in Irish co-operative social housing. The study provided feedback to the householders through direct and indirect energy consumption feedback and indirect temperature profile feedback. The study was carried out to examine if the feedback would elicit any changes in the householder's building operational energy consumption and how the changes in energy consumption from the feedback compared to changes in building operational energy consumption following a building energy efficiency retrofit.

Chapter 7 provides discussion of the results of the thesis and the interrelationships between the operational energy consumption of residential buildings, the people occupying the buildings and the materials used in the construction/retrofit of residential buildings in Ireland as residential buildings move towards nZEB standards. Appendices are also included which provide supportive detail on the research work.

Chapter 2. Literature review

2.1 Introduction

To assess the sustainability of new building and retrofit building designs from an environmental, economic and social perspective, the interrelationships between the operational energy demand practices in buildings, the people occupying the buildings and the materials and technology used in the construction/retrofit of the buildings need to be examined.

To understand the interrelationship between the materials and technology used in the construction of buildings and the operational demand of buildings, the share of embodied energy associated with building materials and technology in a building life span is outlined in Section 2.2.1. Further, in Sections 2.2.2 and 2.2.3, the embodied and operational intensity of various case study building designs and heating systems employed in life cycle assessment studies is presented. The (in)effectiveness of material and technology focused building energy efficiency retrofits is examined in Section 2.3.1. Reasons for differences in the energy consumption between theoretical/numerical models and actual monitored data is examined to understand if the materials and technologies used in the retrofit of the buildings, the operational energy demand practices in buildings and the people occupying these buildings play a role in the reported differences in energy consumption. Following that, Section 2.3.2 elaborates on the prevalence of social dimensions in life cycle retrofit studies to determine if social impacts from changes to building materials and technology following a retrofit are being assessed. Section 2.4 discusses how the use of energy cultures from social sciences can aid in understanding the environmental and social impact from a building energy efficiency retrofit and how the interrelationships between the operational energy demand practices in buildings, the people occupying the buildings and the materials and technology used in the construction/retrofit of the buildings influence the environmental and social impacts. Finally, the effectiveness of energy consumption feedback in reducing the energy consumption of people in buildings and its application in an Irish dwelling context are presented in Section 2.5.

Prof Henrike Rau from Ludwig Maximilian University of Munich and Dr Richard Manton from Engineers Ireland contributed to Section 2.4 regarding the social science literature and selecting the Energy Cultures Framework (ECF) as the framework for investigating the interrelationships between (i) energy efficiency retrofitting, (ii) domestic energy use, (iii) material conditions, and (iv) social and cultural norms of householders and how each of these elements are impacted from a materials and technology focused building energy efficiency retrofit.

2.2 Life Cycle Assessment of New Build Residential Buildings

Recently, several solutions have furnished the building sector which serve to achieve lower operational energy (OE) demand and adequate comfort conditions in a building's life cycle. Given this, more attention has been paid to the environmental impact from the production of the materials and technology used in the solutions for achieving lower OE demand. To understand the interrelationship between the materials and technology used in the construction of a building and the operational demand of a building in a sustainable building design, life cycle assessments are becoming a standard method.

Therefore, carrying out environmental and economic LCA on residential buildings in Ireland, constructed to various energy performance criteria, will aid designers to adapt a sustainable holistic life cycle approach for domestic construction projects going forward. Hence, it is important to assess previous environmental LCA studies conducted on residential buildings to gain a perspective on typical buildings embodied environmental impacts and the factors that influence the embodied.

2.2.1 Embodied Share of Residential Buildings Life Cycle Energy

Table 2.1 summarises a broad range of published environmental LCA studies of residential buildings, in terms of the proportional breakdown of life cycle energy attributed to OE and embodied energy (EE) per square metre of the functional unit floor area used in respective studies [34], [35], [89]–[93], [81]–[88]. In addition, the system boundary utilised, location and climatic conditions of the region are included in Table 2.1. All referenced papers in Table 2.1 used a process based LCA methodology.

The climatic regions are divided into five climate zones (A to E) with buildings in Zone A typically requiring high cooling and low heating needs and buildings in Zone E typically requiring low cooling and high heating needs. The criteria for each zone is based on the amount of heating degree days (HDDs) and cooling degree days (CDDs) experienced at the location [94]. HDDs and CDDs are a measure of how much (°C) and for how long (days) outside air temperature was lower and higher than the base temperature. Using information gathered from an online degree day database [95] and taking 18°C as the base temperature for all climate types, climate zones were assigned to each of the case study locations.

Significant variations in proportional life cycle energy breakdown exist in the literature examined from a (i) life cycle system boundary, (ii) lifespan, (iii) building type, (iv) structure type, (v) location and (vi) material database perspective. Thus, a case study comparison is difficult. As shown in Table 2.1, the contribution of EE to overall energy consumption can range from 5% to 100%.

The contribution of EE to the overall energy consumption can be as low as 0% according to a case study on hypothetical building models in Finland [93]. In this study, 90% of the materials were assumed to be recycled at the end of the case study buildings life cycle and used for a secondary application. The study found that for light weight timber and cross laminated buildings, more energy was saved in the recycling of materials and their secondary application than initially invested into the buildings. Therefore, only the cradle to grave results were considered from this study.

It is worth mentioning that the OE in Table 2.1 accounts for the heating ventilation and cooling (HVAC), hot water, lighting, appliance usage etc. depending on the individual study. The energy with regards to the maintenance, repair, replacement and refurbishment of materials during the operational phase is not included in the values given in Table 2.1. Buildings designed to latest building regulations or passive house standards generally have a lower OE contribution to their life cycle energy. Two notable exceptions were found in buildings constructed in Norway [35] and Sweden [87]. The minimum energy requirement of residential buildings constructed to 2010

Table 2.1: Environmental LCA residential building studies with OE and EE proportions.

Ref.	Building Type		CONS Type	Location	CLI Zone	CONS Year	Area (m^2)	Lifespan (years)	LCB	Percentage of OE (%)	Percentage of EE (%)
[81]	Prefabricated single family units		Wood	Sweden	E	1991/ 1992	130	50	CTGR	83	17
							129			85	15
							138			85	15
[82]	Low energy mid-terrace house	SI experimental building	Timber	Norway	E	1999	110	50	CTGR	72*	28*
		Current BR with SC								90*	10*
		Current BR with exhaust air heat pump								92*	8*
		Previous BR								95*	5*
		Architect 'green' BR								92*	8*
[83]	Passive Apartment	Original EE	Timber	Sweden	E	2001	120	50	CTC	57-60	40-43
		Minimum EE								69-73	27-31
		Maximum EE								56-61	39-44
[34]	3-storey Apartment Block	Prior to EPBD	Concrete	Northern Italy	B		1,050	50	CTGA	86	14
		Current EPBD Standards								81	19
		Borge Solare Standard								53	47
[84]	BIAC Standard House		Light Timber	New Zealand	C		94	100	CTS	74	26
			Concrete							71	29
			SI Timber							57	43
[85]	Terraced House		Concrete	Spain	B		222	50	CTGA	69	31
[35]	Single family house	2010 BR	Wood	Norway	E	UNK	187	50	CTGR	85-89*	11-15*
		Passive BR				UNK	187	50	CTGR	78-83*	17-22*
[86]	Passive House		Concrete/Steel/Timber	Italy	B	UNK	251.6	70	CTC	0	100
[87]	Passive House		Timber	Sweden	E	2010	160	50	CTGA	81**	19**

[88]	Passive House	Solid	Austria	D	UNK	1,351	50	CTGR	77	23
	Low energy house	Timber				1,341			77	23
	Low energy house	Timber				1,094			73	27
	Low energy house	Solid				901			72	28
	Low energy house	Solid				683			75	25
[89]	Single Family House	Light Timber	USA	B	UNK	255	65	CTGR	79	21
	Single Family House	Concrete	Switzerland	E	UNK	191	65	CTGR	49	51
[90]	2-bedroom apartment	Concrete	Portugal	A	1940’s	367	75	CTS	80	20
	3-bedroom apartment					472			80	20
	5-bedroom apartment					1041			73	27
[91]	Detached house	Concrete	Italy	B	UNK	443	50	CTGR	77	23
	Multi-dwelling					1827			79	21
	Office					3353			85	15
[92]	Apartment Building	Concrete	Italy	B	UNK	610	70	CTC	26	74
[93]	Detached house	LWT	Finland	E	UNK	96	50	CTGR	85	15
		CLT							77	23
		Concrete							67	33
		Steel							72	28
	Row house	LWT	Finland	E	UNK	316	50	CTGR	85	15
		CLT							76	24
		Concrete							69	31
		Steel							72	28
	Town house	LWT	Finland	E	UNK	475	50	CTGR	84	16
		CLT							74	26
		Concrete							68	32
		Steel							72	28
	Apartment block	LWT	Finland	E	UNK	1775	50	CTGR	83	17
		CLT							73	27
		Concrete							67	33
		Steel							70	30

Abbreviations		
BR: Building Regulations	CTGR: Cradle-to-Grave	SC: Solar Collectors
CLI: Climate	CTS: Cradle-to-Site	SI: Super Insulated
CON: Construction	CLT: Cross Laminated Timber	UNK: Unknown
CTC: Cradle-to-Cradle	LCB: Life Cycle Boundary	*Values estimated from graphs
CTGA: Cradle-to-Gate	LWT: Light Weight Timber	**Total primary energy, non-renewable energy

Norwegian Building Standards is 120 + 1600/m^2 of heated floor area kWh/m^2/yr [96]. This is more than the 2007 Irish Building Regulations standards [97] (Table 1.1) and only achieves a BER of B2 in Ireland. On the other hand, the OE of the residential building constructed in Sweden was based on the results of the OE of two passive buildings monitored for a year [98]. The OE of the houses was found to be 27.5% to 32.4% higher than estimated due to the behaviour of the inhabitants.

Of the other reviewed papers in Table 2.1, only two monitored the OE of their case study building for a year [86], [92]. An Italian passive house net-energy exporter residence underestimated its energy consumption by 14.4% [86]. The estimated energy consumption was not reported by Cellura [92]. All other reviewed papers made use of simulation packages to calculate the OE of their respective case studies.

The most common climatic zone of the reviewed papers in Table 2.1 is Zone E which is the climatic zone Ireland falls within. An average EE contribution of 21% is calculated for the published studies. This is calculated assuming a 60-year lifespan for a residential building (which is taken as standard in Ireland) for the case studies in Zone E and assuming a linear relationship between a building's lifespan and its overall OE life cycle energy contribution. Note that reoccurring energy and system boundary differences are not considered in calculating the average EE contribution of 21%.

2.2.2 Embodied Energy and Global Warming Potential Building Intensities

Global warming potential (GWP) is a relative measure of how much heat a GHG traps in the atmosphere [99]. Table 2.2 summarises a broad range of published environmental LCA studies, in terms of EE and embodied global warming potential (EC) (also known as embodied carbon) per square metre of the functional unit floor area used in respective studies [34], [35], [90]–[93], [100]–[105], [81], [106]–[108], [82]–[86], [88], [89].

The number of LCA studies on buildings has increased in recent years due to growing popularity and significance of building LCA. All referenced papers in Table 2.2 used a process based LCA methodology apart from Heinonen's [106] study, which used a hybrid based methodology.

The results of studies conducted in climate Zone E revealed EE intensities ranging from 1731 to 23342 MJ/m^2 [35], [81]–[83], [89], [93], [100], [104], [108]. The large range in EE intensity results was related to the system boundaries of the studies, the construction types and standards that each of the buildings were constructed to. The average EE intensity of the buildings in Zone E was 4494 MJ/m^2. System boundary, building construction type and standard differences were not considered for this average of 4494 MJ/m^2.

Studies conducted in Scandinavian countries found EE intensities ranging from 1800 MJ/m^2 to 7559 MJ/m^2 [35], [81]–[83]. The large differences in results were also related to the system boundaries of the studies and the building standards that each of the buildings were constructed to.

Terraced, semi-detached and detached houses constructed in the United Kingdom (UK) showed a similar EE intensity (4900 MJ/m^2 to 5600 MJ/m^2) [104] to the pre-fabricated timber homes constructed in Sweden (4320 MJ/m^2 to 5040 MJ/m^2) [81]. A separate study of terraced, semi-detached and detached UK houses found an EE intensity ranging from 351 MJ/m^2 to 352 MJ/m^2 [108]. This is significantly less than the values of all other studies. These results were considered incorrect based on the list of materials used for constructing the houses and were not considered for further comparisons.

Local building construction methods, functional units and building design regulations can have a big impact on the EE intensities of single family residential studies [86], [89], [91]. In this regard, the EE intensity difference between a single family house constructed in New Jersey, USA in comparison to a house constructed in Switzerland was 10,908 MJ/m^2 [89]. The functional units of these studies were based on the heated floor area of each building. However, if the gross floor area of both houses was taken as the functional unit, the difference in EE intensity between the two buildings would only be 979 MJ/m^2. The EE intensities of both buildings were large due to the superstructure of the buildings. Each building had a garage/basement which increased the amount of concrete required for the building's superstructure. The Switzerland house was constructed to a higher energy standard meaning that more energy was required for the building envelope materials. A detached family house in Italy also had a high EE intensity (12,955 MJ/m^2) due to the superstructure [91]. The superstructure consisted of a the three-storey concrete vertical envelope which had the highest contribution to the assessed environmental indicator [91].

For houses constructed to a passive standard, EE intensities ranged from 6086 MJ/m^2 to 13,869 MJ/m^2 when the system boundary for the houses is taken as cradle-to-grave [35], [83], [86], [88]. A passive house constructed in Italy had an EE intensity of 13,869 MJ/m^2 [86]. However, this building was a net energy exporter as it produced more energy on-site than it imported from external sources. This very large EE intensity was due to several factors. The superstructure of the building had a significant impact as the residence was constructed in a seismic area. The amount of concrete and cement generally used for a typical dwelling increases by 20% for protection against earthquakes [86]. The basement of the building was the largest contributor of the building components to the EE intensity. However, the floor area of the basement was not included in the functional unit of the study (1 m^2 of liveable floor area for a period of one year). The western façade of the building was covered in aluminium as protection for the building. Aluminium is a very energy intensive material with a primary energy intensity of 218 MJ/kg [109]. This highlights the importance of a designer's role in sustainability by selecting appropriate 'green' materials. This was also stressed by a case study where the same OE was achieved by a house of EE intensity ranging from 3015 MJ/m^2 to 4810 MJ/m^2 [83].

Therefore, it is important to evaluate different design strategies of a building. This allows for assessing the impact various design strategies of a building has on the EE and OE. Of the reviewed studies (Table 2.2), only four other papers compare different design strategies of the same building [34], [35], [93], [100].

Four different superstructure designs (light weight timber, cross laminated timber, concrete and steel) of four building types (detached house, row house, town house, and apartment block) were evaluated in hypothetical building models in Finland [93]. The results showed that buildings constructed to have steel superstructures were the optimum designs in terms of life cycle energy. However, only one environmental indicator (energy) was evaluated in this study.

A case study of a 3-story apartment block found that an increase in EE investment from 4007 MJ/m^2 to 4158 MJ/m^2 reduced the OE of the life cycle energy consumption from 87% to 16%. This was primarily due to the installation of a geothermal heat pump [34] with the EE investment paid back in less than a year.

Table 2.2: EE and EC intensities of published residential environmental LCA.

Ref.	Building Type		CONS Type	Location	CLI Zone	CONS Year	Area (m^2)	Life-span (years)	LCB	EE (MJ/m^2)	EC ($kgCO_{2eq}/m^2$)
[81]	Prefabricated single detached units		Wood	Sweden	E	1991	130	50	CTGR	5,220	-
							129			4,932	-
							138			4,176	-
[82]	Low energy mid-terrace house	SI experimental building	Timber	Norway	E	1999	110	50	CTGR	4,424*	-
		Current BR with SC								2,470*	-
		Current BR with exhaust air heat pump								2,005*	-
		Previous BR								1,800*	5
		Architect ‘green’ BR								2,470*	8
[34]	3-storey Apartment Block	Prior to EPBD	Concrete	Italy	B		1,050	50	CTGA	4,007	-
		Current EPBD Standards								4,158	-
		Borge Solar Standard								4,428	-
[83]	Passive Timber Terraced House		Original EE	Sweden	E	2001	120	50	CTC	4,383-4,736	-
			Minimum EE							3,015-3,461	-
			Maximum EE							4,266-4,810	-
[84]	BIAC Standard Single Storey House		Light Timber	New Zealand	C		94	100	CTS	4,425	-
			Concrete							4,764	-
			Super-insulated Timber							5,041	-
[104]	Apartment (3-storey)		Concrete	UK	E	2006	50	60	CTS	6,600	480
	Apartment (4-storey)						50			6,300	460

	Terraced					68			4,900	370
	Semi-detached					73			5,600	425
	Bungalow					76			8,200	620
	Detached					125			5,500	410
[100]	Semi-detached	Light Timber	UK	E	2008	65	100	CTS	-	493
		Medium Concrete							-	512
		Medium-heavy Concrete							-	539
		Heavy Concrete							-	567
[105]	Semi-detached	Concrete	Ireland	E		105	60	CTS	-	369
	Apartment					75			-	299
[101]	Singe-landed house	Clay & Bricks	Indonesia	A	1984	55	40	CTS	837	-
		Concrete							818	-
[102]	Passive House	Adobe	India	A	2009	94	50	UNK	2,299	1,000
[85]	Terraced House	Concrete	Spain	B	2009	222	50	CTGA	5,687	529
[103]	VAR	VAR	Worldwide	VAR	2010	VAR	VAR	VAR	3,600-8,760	-
[107]	Semi-detached	-	UK	E	2010	100	-	UNK	-	550
[106]	Residential Area	Concrete	Finland	E	2011	70,000	25	CTGR	-	3,200
[35]	Two-storey single family house	Timber 2010 BR	Norway	E	UNK	187	50	CTGR	6,608-7,238*	387-414
		Timber Passive BR							7,552-8,181*	441-468
[86]	Passive House	Concrete/Steel/Timber	Italy	B	UNK	251.6	70	CTC	13,869	1009
[88]	Residential building	Solid Passive	Austria	D	UNK	1351	50	CTGR	11,864	794
		Timber low energy				1341			14,624	595
		Timber low energy				1094			16,414	840
		Solid low energy				901			15,267	982
		Solid low energy				683			15,068	943
[108]	Detached	Concrete	UK	E	UNK	130	50	CTC	352	261
	Semi-Detached					90			351	283
	Terraced					60			352	280

[89]	Single Family House	Light Timber	USA	B	UNK	255	65	CTGR	12434	583
	Single Family House	Concrete	Switzerland	E	UNK	191	65	CTGR	23342	1107
[90]	2-bedroom apartment	Concrete	Portugal	A	1940’s	367	75	CTS	4176	272
	3-bedroom apartment					472			4082	262
	5-bedroom apartment					1041			3746	239
[91]	Detached house	Concrete	Italy	B	UNK	443	50	CTGR	12955	1050
	Multi-dwelling					1827			8668	674
	Office					3353			7349	575
[92]	Apartment Building	Concrete	Italy	B	UNK	610	70	CTC	27440	-
[93]	Detached house	LWT	Finland	E	UNK	96	50	CTGR	3356	-
		CLT							5657	-
		Concrete							4857	-
		Steel							3830	-
	Row house	LWT	Finland	E	UNK	316	50	CTGR	2634	-
		CLT							4586	-
		Concrete							3498	-
		Steel							3015	-
	Town house	LWT	Finland	E	UNK	475	50	CTGR	2423	-
		CLT							4496	-
		Concrete							3156	-
		Steel							2754	-
	Apartment block	LWT	Finland	E	UNK	1775	50	CTGR	2112	-
		CLT							3749	-
		Concrete							2434	-
		Steel							2328	-

Abbreviations

BR: Building Regulations
CLI: Climate
CONS: Construction
CTC: Cradle-to-Cradle
CTGA: Cradle-to-Gate
CTGR: Cradle-to-Grave
CTS: Cradle-to-Site
CLT: Cross Laminated Timber
LCB: Life Cycle Boundary
LWT: Light Weight Timber
SC: Solar Collectors
SI: Super Insulated
UNK: Unknown
VAR: Various
*Values estimated from graphs

A New Zealand case study invested 616 MJ/m^2 to convert from a light timber construction house to a super-insulated timber construction [84]. The EE investment reduced the OE proportion of the building's life cycle from 74% to 57%, utilising the same heating system in both analysis The EE investment was paid back within 11 years through the OE reduction. Another study showed that to change from the Norwegian 2010 Building Regulations to a Passive Building Standard for four different heating scenarios required an investment ranging from 943 MJ/m^2 to 1259 MJ/m^2 [35]. These values were estimated from a graph and, as such, pay back times were not determined.

2.2.3 Heating System Design Strategies in Building Life Cycle Assessments

Table 2.3 summarises a broad range of published environmental LCA studies, in terms of the building type, location, climatic zone, heating system, installed renewable technologies, and the impact those aspects have on the buildings OE and OC [32], [34], [87]–[93], [100]–[102], [35], [108], [110]–[113], [39], [81]–[86]. The OE in Table 2.3 accounts for the HVAC, hot water, lighting, appliance usage etc. depending on the individual study. However, the energy with regards to the maintenance, repair, replacement and refurbishment of materials and technology during the operational phase is not included in the values given in Table 2.3.

Reviewed LCA studies concerned buildings with heating systems based on gas [32], [34], [85], [88]–[91], [100], [113], electricity [35], [82], [84], [90], [101], [102], [113], ground and air source heat pumps [34], [35], [39], [82], [86], [88], [89], [92], [110], [111], district heating [83], [87], [93], [110]–[112] and renewable technologies [32], [35], [39], [82], [83], [85], [86], [88], [92].

Multiple studies on low energy and passive buildings are available in the literature [32], [35], [92], [93], [102], [111], [39], [82]–[84], [86]–[89]. Their annual OE and OC usage ranged from -167 MJ/m^2 to 1025 MJ/m^2 and -9 kgCO$_{2eq}$/m^2 to 51 kgCO$_{2eq}$/m^2, respectively. Single residential building studies designed to latest building regulations or passive house standards generally had a lower OE contribution to their whole life cycle energy usage.

The OE of a residential building constructed in Sweden was based on the results of the OE of two passive buildings monitored for a year [98]. The measured OE of the houses was found to be 27.5% to 32.4% higher than estimated, due to the behaviour of the inhabitants.

Among the other reviewed literature in Table 2.3, only three monitored the OE of the building [86], [87], [92]. The case study examined by Proietti [86] was a net-energy exporter residence which underestimated its predicted energy consumption by 14.4%. Albeit, it had the smallest OE and OC impact of the reviewed literature. This house was a net energy exporter as it produced more energy on-site than it imported from external sources due to a large amount of renewable technology installed. The space and water heating system of this house comprised an electric heat pump combined with mechanical ventilation, 6 m^2 of solar collectors and 68 m^2 of photovoltaics (PV).

Of the 25 reviewed studies, only three monitored the whole house energy consumption of the case study buildings [86], [87], [92], three simulated space heating [34], [101], [102], four simulated whole house energy consumption including appliances [39], [82], [110], [111], seven simulated whole house energy consumption including appliances from multiple simulation/statistical sources [84], [88], [90], [91], [93], [108], [113], one simulated whole house energy consumption from multiple simulation/statistical sources without accounting for hot water requirements [100], four simulated whole house energy consumption but do not explicitly state they account for appliances in electricity usage [35], [81], [83], [112] and three simulated whole house energy consumption excluding appliances [32], [85], [89].

In cold climates (e.g. Scandinavian countries), heating systems installed in the reviewed studies included electrical [35], [39], [82], [110], [111] or district heating [83], [87], [93], [110], [111] combined with mechanical ventilation and heat recovery (MVHR) systems. In the UK studies [100], [108], gas heating systems were used due to the availability of this resource. Gas is the main source of fuel for domestic space and water heating in the UK, accounting for 84% and 80% of the energy consumption, respectively [108].

Examining which heating system/fuel source is the optimum system design strategy for residential buildings among the reviewed studies of Table 2.3 is difficult due to differences in multiple factors that effect a building design including location, climate, cost, available resources, etc. With a heating system design solution having a big impact on the environmental and economic life cycle of buildings, it is important to

Table 2.3: Environmental LCA studies of residential buildings with OE and OC proportions.

Ref.	Building Type		Construction Type	Location	CLI Zone	Heating System	SC/PV	Ventilation	OE (MJ/m^2/yr)	OC (kgCO$_{2eq}$/m^2/yr)	OE (%)	OC (%)
[81]	Prefabricated single detached units		WD	SWE	E	UNK	-	MVHR	511	-	84	-
									533	-	84	-
									461	-	84	-
[82]	MT LEH	SI building	TIM	NOR	E	GSHP	PV (22m^2)	MVHR	227	-	72	-
		Current BR with SC				EL	SC	MVHR	409	-	90	-
		Current BR with EAHP				EL		EAHP	475	-	92	-
		Previous BR				EL		MV	605	-	95	-
		Architect 'green' BR				EL		MV	543	-	92	-
[34]	AP Block	Prior to EPBD	CON	North ITL	B	GB	-	AC	486	-	86	-
		Current EPBD Standards				CGB	-	AC	360	-	81	-
		Borge Solare Standard				GHP	-	AC	101	-	53	-
[83]	PH TH	Original EE	TIM	SWE	E	CHP DH	SC	MVHR	220	-	60	-
		Min EE							220	-	64	-
		Max EE							220	-	59	-
[84]	BIAC Standard Single Storey House		TIM	NZL	C	EL	-	UNK	126	-	74	-
			CON				-		115	-	71	-
			TIM				-		67	-	57	-
[100]	SD		TIM	South UK	E	CGB	-	NV/MV	-	25-28	-	84-85

			CON				-		-	22-25	-	81-84
			CON				-		-	21-23	-	79-81
			CON				-		-	20-22	-	78-80
[101]	Singe-landed house		Clay & Bricks	IDN	A	EL	-	AC	274	-	87	-
			CON				-		311	-	93	-
[102]	PH		Adobe	IND	A	EL	-	NV	210	-	Unk	-
[85]	TH		CON	ESP	B	GB	SC	AC	256	15	69	59
[35]	Two-storey SFH	2010 BR	TIM	NOR	E	EL	-	MVHR	1025*	25*	77*	89*
						EL & WD	-		846*	23*	75*	86*
						EL	SC		886*	22*	73*	86*
						EL & AWHP			748*	20*	71*	85*
		PSR				EL			729*	18*	68*	83*
						EL & WD			665*	17*	66*	81*
						EL	SC		589*	15*	61*	78*
						EL & AWHP			561*	15*	61*	78*
[86]	PH		CON/STE/TIM	ITL	B	EL HP	SC (6m^2), PV (68m^2)	MVHR	-173	-9	0	0
[88]	PH		Solid	AUT	D	AAHP	-	MV	516	35.6	71	69
	LEH		TIM			Gas	-	-	806	50.8	82	81
	LEH		TIM			Gas	-	-	723	45.6	74	73
	LEH		Solid			Gas	SC (50m^2)	-	626	39.9	70	67
	LEH		Solid			Gas	SC (50m^2)	-	725	45.9	74	71
[87]	PH		TIM	SWE	E	DH & WD stove		MVHR	UNK	UNK	81*	56*
[108]	Detached		CON	UK	E	UK Domestic Energy use	-	UNK	678	62	99	88
	SD						-		809	74	99	89
	TH						-		1009	94	99	92
[89]	SFH		TIM	USA	B	GB and ASHP	-	MVHR	740	33	79	79

	SFH	CON	CHE	E	GSHP	-	MVHR	348	4	49	20
[90]	2 BD AP	CON	PRT	A	EL and gas	-	UNK	269	14	20	80
	3 BD AP							214	11	20	77
	5 BD AP							136	7	27	69
[91]	Detached	CON	ITL	B	Gas-fired	-	UNK	876	52	77	71
	Multi-dwelling				Gas-fired	-		640	40	79	75
	Office				AC	-		836	54	85	82
[92]	AP building	CON	ITL	B	GSHP, GB	SC (10 m^2), PV (150 m^2)	MVHR	174	-	24	-
[93]	Detached house	TIM	FIN	E	DH	-	MVHR	275	-	83	-
		TIM						274	-	75	-
		CON						97	-	52	-
		STE						99	-	58	-
	Row house	TIM	FIN	E	DH	-	MVHR	220	-	83	-
		TIM						218	-	75	-
		CON						76	-	53	-
		STE						79	-	49	-
	Town house	TIM	FIN	E	DH	-	MVHR	194	-	83	-
		TIM						193	-	74	-
		CON						68	-	54	-
		STE						70	-	58	-
	AP block	TIM	FIN	E	DH	-	MVHR	150	-	81	-
		TIM						148	-	72	-
		CON						49	-	52	-
		STE						54	-	56	-
[110]	MSRB	CLT	SWE	E	CHP & Heat Only Boiler	-	MVHR	673.2	-	91.8	-
					HP	-		633.6	-	92.2	-
		TIM, Beams & Column			CHP & Heat Only Boiler	-	MVHR	691.2	-	90.8	-
					HP	-		648	-	91.3	-

			TIM, Modular			CHP & Heat Only Boiler	-	MVHR	691.2	-	91.5	-
						HP	-		648	-	91.9	-
[111]	MSRB	Conventional	CLT	SWE	E	CHP & Heat Only Boiler	-	MV	-	7.2	-	75
		Low Energy					-	MVHR	-	6.3	-	70.3
		Conventional				HP		MV	-	8.4	-	77.8
		Low Energy						MVHR	-	6.8	-	71.8
		Conventional	TIM, Beams & Column			CHP & Heat Only Boiler	-	MV	-	7.2	-	69.4
		Low Energy					-	MVHR	-	6.3	-	65.6
		Conventional				HP		MV	-	8.4	-	72.5
		Low Energy						MVHR	-	6.9	-	67.6
		Conventional	TIM, Modular			CHP & Heat Only Boiler	-	MV	-	7.2	-	72.1
		Low Energy					-	MVHR	-	6.3	-	68.5
		Conventional				HP		MV	-	8.4	-	75.1
		Low Energy						MVHR	-	6.9	-	70.4
[39]	nZEB SFH		TIM	NOR	E	AWHP	SC (8.32m^2), PV	MVHR	-115	-4.2	0	0
[112]	MSRB		TIM	DEU	E	DH CHP	-	UNK	372.1	22.4	58.1	68.3
[113]	SD		Stone/Brick	PRT	A	EL, Gas, LPG	-	UNK	270.7*	19.7*	81*	78*
	AP		Stone/Brick						254.8*	18.6*	83*	80*

Abbreviations

AC: Air Conditioning
AAHP: Air-to-Air Heat Pump
AWHP: Air-to-water heat pump
AP: Apartment
BD: Bedroom
EAHP: Exhaust Air Heat Pump
GB: Gas Boiler
GHP: Ground Heat Pump
GSHP: Ground Source Heat Pump
HP: Heat Pump
PS: Passive Regulations
PV: Photovoltaics
SC: Solar Collectors
SD: Semi-Detached
SFH: Single Family House

BR: Building Regulations
CLT: Cross Laminated Timber
CGB: Condensing Gas Boiler
CHP: Combined Heat and Power
CON: Concrete
DH: District Heating
EL: Electricity
LEH: Low Energy House
LPG: Liquefied Petroleum Gas
MV: Mechanical Ventilation
MVHR: Mechanical Ventilation with Heat Recovery
NV: Natural Ventilation
PH: Passive House
SI: Super insulated
STE: Steel
TH: Terraced House
TIM: Timber
UNK: Unknown
WD: Wood
*Total primary energy, non-renewable energy

assess the effectiveness of multiple design solutions in a comprehensive manner. Among the reviewed studies in Table 2.3, only one study investigated the impact different fuel source heating strategies had on the life cycle energy and GWP usage of the building [35]. Furthermore, the economic feasibility of the design solutions was not evaluated.

2.2.4 Life Cycle Analysis of Irish Residential Buildings

For Irish residential buildings, which are the focus of this thesis, only one study on new build Irish residential buildings was found in the literature [105]. An Irish semi-detached case study dwelling was found to have a slightly lower EC intensity than similar studies in the UK [100], [104], [107]. The difference in EC intensity might be due to slight variations in production methodologies of certain building materials and technologies or minor differences in building code regulations [114], [115].

In summary, a number of factors from a life cycle perspective can influence the interrelationship between the materials used in the construction of a building and the operational demand of a building from an environmental perspective including the (i) life cycle system boundary, (ii) building lifespan, (iii) building design regulations, (iv) building typology, (v) structure type, (vi) heating system, (vii) location and (viii) material database. Based on reviewed single-family residential buildings case study buildings designed to a low energy performance, passive or nZEB standards, the EE impacts can range from 2299 MJ/m^2 to 16414 MJ/m^2. Furthermore, the EE percentage of the life cycle impact can range from 17% to 100%. In addition, the EC impacts can range from 414 $kgCO_{2eq}/m^2$ to 1009 $kgCO_{2eq}/m^2$.

Thus with LCA mandatory in building design in several EU countries [41], a lack of LCA studies in relation to Irish residential buildings and the large range of environmental impacts for buildings designed to a high energy performance standards, a notable gap in the literature is identified. With significant construction of residential buildings in Ireland in the preceding decade [116] and Ireland requiring at least an additional half a million new housing units by 2040 [72], a standardised comprehensive environmental LCA examining the life cycle breakdown and more accurate environmental intensity values from an Irish context is necessary. This is to examine the interrelationship between the materials used in the construction of a building and the operational demand of a building to understand how the embodied share of a building's life cycle is changing due to revisions in the building regulations to achieve nZEB standard. Additionally, to assess whether any environmental 'hot spots' from materials and technologies used in past and present construction practices need to be altered to reduce the environmental impact of the Irish building construction sector. This is examined in **Chapter 3**. Furthermore, from reviewing the studies of Table 2.1, Table 2.2 and Table 2.3, different thermal fabric and heating system design strategies play a significant role in the environmental life cycle impact of residential buildings. The effects of different thermal fabric and heating systems design strategies for new build Irish nZEB residential buildings are also examined in **Chapter 3**. The design strategies are examined through the lens of the cost-optimal methodology framework and life cycle analysis to assess the design strategies.

2.3 Energy Efficiency Retrofits of Residential Buildings

Improving the energy efficiency of buildings via technocentric retrofits is seen as one of the key mitigation measures to reducing the energy demand and carbon emissions of the built environment in Ireland [77]. However, while material and technology focused energy efficiency retrofits are effective in theory, the energy savings estimated by statistical or engineering models can often be inaccurate. The (in)effectiveness of material and technology focused building energy efficiency retrofits is examined in Section 2.3.1. Reasons for differences in the energy consumption between theoretical/numerical models and actual monitored data is examined to understand if the materials and technologies used in the retrofit of the buildings, the operational energy demand practices in buildings and the people occupying these buildings play a role in the reported differences in energy consumption. Following that, Section 2.3.2 elaborates on the prevalence of social dimensions in life cycle retrofit studies to determine if social impacts from changes to building materials and technology following a retrofit are being assessed.

2.3.1 The (In)effectiveness of Energy Efficiency Retrofits

The inaccuracy of energy savings estimated by statistical or engineering models is often explained by what has come to be known as the rebound effect. Energy efficiency improvements often result in making energy services cheaper. This in turn may cause the consumption of these services to increase [117]. For example, if a householder invests in installing a more efficient space heating system in their house, the householder may choose to offset some of their savings by heating their house to a higher temperature than before the boiler was installed. This is known as a direct rebound effect. An indirect rebound effect would be the result of spending the savings made through installing the boiler on an energy intensive service, such as an overseas flight. The sum of direct and indirect rebound effects represents economy wide rebound effects [117]–[119]. Compared to studies on indirect rebound effects, the direct rebound effect is the more commonly examined topic in literature studies. Although, the number of studies examining both direct and indirect rebound effects is growing [58], [120]–[125].

As household energy consumption represents a significant portion of the world's energy consumption, many studies have focused on the rebound effect related to space and water heating [126]–[133], space cooling [134], [135], electricity usage [128]–[130], [134]–[137], gas usage [127], [131] and domestic appliances [138].

The direct rebound effect can be estimated using quasi-experimental and econometric approaches [117], [118]. Quasi-experimental studies examine the before and after impact of energy improvements on the demand for energy or energy services. For a quasi-experimental study, there needs to be two scenarios; (i) the energy usage without the change in energy efficiency improvements and (ii) the energy usage with the change in energy efficiency improvements that does not result in a change in behaviour.

On the other hand, econometric studies use secondary data sources to estimate the elasticity of the demand for energy, energy efficiency and/or energy services at different levels of aggregation [117], [118]. The elasticity refers to the percentage change in one variable following a percentage change in another whilst holding the other measured variables constant. Econometric studies use cross-sectional, time series and/or panel data in their analysis. Both quasi-experimental and econometric study approaches and their respective methodological challenges are discussed in [117]–[119].

2.3.1.1 Econometric Model Direct Rebound Effect Studies

In econometric models, the direct rebound effect can be estimated based on the (i) elasticity of the demand for energy with respect to energy efficiency, (ii) the elasticity of the demand for useful work with respect to energy efficiency, (iii) the elasticity of the demand for useful work with respect to the price of useful work, (iv) the elasticity of the demand for useful work with respect to the price of energy and (v) the elasticity of the demand for energy with respect to the price of energy [117].

For econometric models that do not have data for before and after an energy saving intervention, relationships (iv) and (v) allow models to assume that a change in energy price is representative of an energy saving measure. For this to be valid, an econometric model assumes that consumers respond in the same way to a decrease in energy prices as they do to an increase in energy efficiency (and vice versa). The model also assumes that energy efficiency is unaffected by changes in energy prices. The majority of econometric rebound effect studies rely on relationships (iv) and (v) as the direct rebound effect can be estimated based on energy price data which can be matched with data from secondary sources that are more freely available [117].

The secondary sources used for developing direct rebound effect econometric models generally use information on technical characteristics of the buildings (e.g. floor area, structural elements, heating systems), local climate (e.g. HDDs, CDDs, wind velocity), socio-economic (GDP, household income etc.), energy and building market prices (e.g. energy prices, building value, retrofit costs etc.), demographics (number of tenants, age profiles etc.) and energy usage practices (e.g. internal set-points, number of rooms heated, washing loads etc.).

Secondary data sources are often sourced from national organisation databases or national surveys. Thus, direct rebound econometric model studies often have large sample sizes. This allows studies to generate models that are representative of different aggregation levels (country, region, household) and/or different socio-economic groups to examine how changes to factors such as energy pricing or income levels effect energy consumption. Studies examining the impact of increasing and decreasing energy prices allow policy makers to examine the potential impacts of policy decisions. Studies on different aggregation levels (country, region, household) and/or different socio-economic groups have been carried out on the UK [126], France [126],

[127], [139], Italy [126], Sweden [126], Norway [128], Spain [136], USA [129], [130], Canada [131], [140] and China [135]. Some econometric models have used formulae used in engineering building energy consumption models to estimate energy consumption as part of their secondary data sources [132]–[134], [137], [141]. Econometric models have found the rebound effect to range from 15% to as high as 81% (Table 2.4)

Table 2.4: The estimated rebound effect of various econometric models for multiple countries

Ref.	Energy Consumption	Fields in Model	Country	Rebound Effect (%)
[129]	SH	CLI, BU, SCD, M, EP	USA	43.4-43.7
[130]	SH	CLI, BU, SCD, M, EP	USA	43.4-43.7
[137]	SH & DHW	CLI, BU, SCD, M, EP	USA	22.8
[128]	SH	CLI, BU, SCD, M, EP	Norway	15-55, AVG: 21
[140]	SH	CLI, BU, SCD, M, EP	Canada	29-47, AVG: 39
[126]	SH & DHW	CLI, BU, M	France, Italy, Sweden and UK	Short run: 6-21 Long run: 17-35
[134]	SH	CLI, BU, SCD, M, EP	USA	52-81
[131]	SH & DHW	CLI, BU, SCD, M, EP	Canada	Short run: 10-17 Long run: 35-60
[132]	SH	CLI, BU, SCD, M, EP	Austria	24-29
[133]	SH	CLI, BU, SCD, M, EP	Austria	20
[136]	Electricity	CLI, SCD, M	Spain	Short run: 35 Long run: 49
[135]	Electricity	CLI, BU, M	China	71.5
[142]	SH & DHW	CLI, BU, SCD, M, EP	Netherlands	27-43
[127]	SH, DHW and CK	CLI, BU, Market	France	Short run: 60 Long run: 63

Abbreviations

AVG:
BU: Buildings
CLI: Climate
CK: Cooking
DHW: Hot Water Heating
EP: Energy Practices
M: Market
SCD: Social Demographic
SH: Space Heating

Multiple reasons have been found for differences in the size of rebound effect. Nesbakken [128] and Guertin et al. [140] came to a similar conclusion as Klein [129] in that low-income households were more susceptible to increasing energy prices than higher income groups. Nesbakken [128] found that low income houses (linked to electricity only heating systems) experienced a rebound effect of 55% whereas the entire sample experienced an average rebound effect of 21%. Guertin et. al [140] estimated a rebound effect of 47% for gas and electrically heated Canadian houses.

The rebound effect reduced to 29% for high income houses with the sample average rebound being 39%.

O'Broin et. al [126] examined how increasing energy prices would affect the energy demand of four EU countries [126]. The study found that despite annual increases in energy of up to 3% until 2050, four EU countries would see a reduction in energy demand due to building technical progress. However, the study found that to offset the rebound effect and achieve the 2050 target of building consumption of less than 30 kWh/m^2/year, energy prices would need to increase by 10% annually.

Aydin et. al [142] examined the elasticity of demand for a particular energy service with respect to energy efficiency in retrofitted residential Dutch dwellings. The results indicated a rebound effect for tenants ranging from 41% to 56% and 27% to 43% for owner-occupied dwellings.

A study on the direct rebound effect of residential gas demand in France found that a 1% reduction in gas price would result in a direct rebound effect of approximately 60% in the short run and 63% in the long run [127]. The study concluded that a policy shift from technically oriented efficiency programmes and towards a mixture of renovation and behavioural changes is required.

2.3.1.2 Quasi-experimental Direct Rebound Effect Studies

For a quasi-experimental study, there needs to be two scenarios. The energy usage without the change in improved energy efficiency and the energy usage with the change in improved energy efficiency that does not result in a change in behaviour. Limitations associated with these studies include using before and after scenarios without a control group or controlling for confounding variables, selection bias, small sample sizes, high variance in results, error associated with estimates, large variation independent variable both within and between studies and short study periods [117]. In addition, studies have failed to distinguish between how much of the rebound effect is accounted for by (i) the shortfall in estimating the energy savings relative to the actual savings, (ii) temperature take back from the physical changes to the building and (iii) temperature take back from behavioural changes of the householders in operating the building [117].

Despite these limitations, a quasi-experimental study is the most common approach to estimating the direct rebound effect and how much of the rebound is associated with temperature take back and behavioural change [118]. Quasi-experimental direct rebound effect studies involve either econometric models or engineering models or a combination of both.

A literature review of quasi-experimental studies on the rebound effect of space heating was conducted building on the work of previous reviews [118]. Galvin [143] reviewed the different approaches used in literature to define the rebound effect and discovered there to be incorrect comparisons made across studies due to differences in approaches. The study found the main metrics used to determine the rebound effect, in relation to domestic heating consumption, to be (i) energy efficiency elasticities of energy services (or of energy), (ii) comparisons of energy savings shortfall with expected energy savings, (iii) comparison of actual post-retrofit (or new build) consumption with design consumption and (iv) comparison of actual consumption with energy consumption where there is no retrofit or new build [143].

Galvin [143] defined three metrics to use when evaluating thermal retrofits; rebound effect (RE), energy savings deficit (ESD) and energy performance gap (EPG). The RE, ESD and EPG are shown in equations 2.1 to 2.5. For the three metrics, ACT_{PRE} is the actual energy consumption before the energy efficiency measure, ACT_{POST} is the actual energy consumption after the energy efficiency measure, THE_{PRE} is the theoretical energy consumption before the energy efficiency measure and THE_{POST} is the theoretical energy consumption after the energy efficiency measure.

The rebound effect (RE) is defined as the energy elasticity of demand for energy services (or energy) and is calculated for an individual dwelling [144] by:

$$RE = 1 + {\ln(\frac{ACT_{PRE}}{ACT_{POST}})}\Big/{\ln(\frac{THE_{PRE}}{THE_{POST}})} \tag{2.1}$$

The ESD is the shortfall in expected energy savings as a proportion of the expected energy savings. Different studies calculated the expected energy savings based on either the THE_{PRE} or the ACT_{PRE} [143]. To make comparisons across all reviewed building energy efficiency studies, the ESD is calculated based on both methods.

ESD_{THE} is the energy savings deficit with the energy savings based on the THE_{PRE}. ESD_{POST} is the energy savings deficit with the energy savings based on ACT_{PRE} and is calculated by:

$$ESD_{ACT} = \frac{(ACT_{PRE} - THE_{POST}) - (ACT_{PRE} - ACT_{POST})}{(ACT_{PRE} - THE_{POST})} \tag{2.2}$$

$$ESD_{THE} = \frac{(THE_{PRE} - THE_{POST}) - (ACT_{PRE} - ACT_{POST})}{(THE_{PRE} - TH\ \ _{POST})} \tag{2.3}$$

The EPG is the actual energy consumption as a proportion of the theoretical energy demand. EPG_{PRE} and EPG_{POST} is the energy performance gap before and after the energy efficiency measure and is calculated by:

$$EPG_{PRE} = \frac{THE_{PRE} - AC\ \ _{PRE}}{THE_{PRE}} \tag{2.4}$$

$$EPG_{POST} = \frac{THE_{POST} - ACT_{POST}}{THE_{POST}} \tag{2.5}$$

Several studies used engineering energy demand models in comparison with actual energy consumption data [45], [46], [55], [145], [47]–[54]. 17 quasi-experimental direct rebound effect studies are given in Table 2.5. From an Irish perspective, an analysis on the effectiveness of energy efficiency retrofits on 210 Irish gas heated houses which received a grant through the Home Energy Saving (HES) scheme found an estimated 21% reduction in their actual gas consumption. However, the results estimated an ESD_{THE} ranging from 28% to 44% based on a cross sectional data set involving a control group of houses which did not undertake any energy conservation interventions [45].

An Irish study on the oil consumption of 145 houses pre-retrofit revealed that houses with a lower ENPC were poorer predictors of a household's oil consumption [47]. Based upon the post-retrofit data collected, some of the main reasons for the EPG_{PRE} were believed to be due to the theoretical internal room temperatures not being representative of the actual internal room temperatures and the underestimation of the usage of the secondary heating systems in the households. Based on the comparisons of 37 houses pre-retrofit and post-retrofit, an ESD_{THE} ranging from 73% to 77% was

Table 2.5: Summary of quasi-experimental studies reviewed and estimated EPG, ESD and RE.

Ref.	Energy Usage	Monitoring Period	Target building type	Location	Typology	Sample size	Energy accounts for	*EPG PRE	*EPG POST	*ESD ACT	*ESD THE	*RE
[146]	EL and Wood	PRE: Nov-Feb 84/85 POST: Nov-Feb 85/86	Houses involved in Hood River Conservation Project	USA	EL and wood heated homes	252	Scenario A				*57*	
[48]	EL meter readings	1994-1998	Houses involved in EESOP1	UK	All Types	7923	Scenario D and plug loads	*33*	*21*	*196*	**68**	*56*
					Bungalow	1216		*29*	*13*	*296*	**75**	*68*
					DT	287		*45*	*37*	*127*	**73**	*54*
					Flat	112		*18*	*5*	*-87*	**65**	*60*
					Semi-DT	1981		*42*	*31*	*131*	**77**	*64*
					TR	1080		*26*	*12*	*1824*	**68**	*60*
[48]	EL meter readings		Houses involved in EESOP2	UK	All Types	325	Scenario D and plug loads			**60**		
[49]	Gas meter readings	307 days PRE, 296 POST	Houses involved in the SoP3 programme	UK	Unknown	401	Scenario B			**55**	**51**	
[46]	EL meter readings	2-4 weeks during the winters of 2001 and 2002.	Houses involved in the Warm Front energy efficiency scheme	5 English towns/cities	DT, semi-DT, TR and flat houses	695 PRE, 720 POST	Scenario A	*16*	*-26*	*95*	*98*	*98*

						165 no insulation, 498 wall insulation and loft insulation		*19*	*-40*	*69*	*81*	*82*
[54]	PRE: Energy bills and meter readings. POST: Energy bills and meter readings. Flow and temperature sensors on solar boiler. Electricity boiler monitored. PV generation read from meter	1978-2008		Belgium	End-row House	1	Scenario A	*-44*	*-51*	*-36*	**28**	*-5*
[47]	PRE: Historical oil bills and secondary heating assumed to be 10%, POST: Oil consumption monitored, and solid fuel recorded in notebook	Energy: Nov 2007-Oct 2012, TM: Jan-Sept 2011.	Houses retrofitted in SERVE project	Tipperary, Ireland	Various	37	Scenario B	34	10	-161	73	65
	PRE: Historical oil bills and secondary heating assumed to be 25%							36	10	-239	77	69

[45]	Gas meter readings	PRE: 2007-2008; POST: 2008-2010	Houses involved in Ireland's Home Energy Saving (HES) residential retrofit scheme	Ireland	DT, Semi-DT, TR and flats	210	Gas-Scenario B (Unclear if houses use gas for cooking)			**36±8**
[51]	Meter readings	Energy-2008-2014, TM: Mar & Apr 2013	Low-Income houses involved in the Weather Assistance Program (WAP)	Michigan, USA		Experimental: 2,074 Control: 2,973	Scenario C			
[142]	Gas meter data	2009-2011	Gas-heated involved in government funded programme	Netherlands		Experiment: 605 Control: 4593	Scenario B			**57**
[50]	Generation, storage and distribution of SH and DHW	2009-2014.		Germany	Apartments	30	Scenario B		**5-6**	
						10			**7-13**	
						10				
						10				
						10			**23-28**	
						10				
						10				
[52]	Meter readings	N/A	Low income estates	Belgium	Semi-D, mid and end TR	8	Scenario B	**44**		
					TR	12		**51**		

[147]	PRE: Utility bills; POST: EL and gas meters read daily, heat pump usage monitored with meter	May 2012-Nov 2014		Copenhagen	Single family home	1	Scenario C	*39*	*55*	*1607*	*14*	*-61*
[145]	30 minutes for internal environments. Not specified for energy usage	PRE: 2011-2012, POST: 2012-2013		Hvakso, Denmark	Residential multi-storey	3 multi-storey blocks with each block having 3 floors and 66 flats	Scenario C	-1	-1	2	-2	-1
[55]	Meter readings	2010-2012	Social Housing	Netherlands	All	72376	Scenario B				*30*	
					Heating and hot water retrofit	30749					*38*	
					Envelope retrofit	21035					*42*	
					Window retrofit	15744					*28*	
					Ventilation retrofit	4848					*-152*	
[53]	PRE: Energy bills and meter readings. POST: Meters for gas, electricity, water, PV and solar thermal with remote data collection	PRE: August-November 2009; POST: Mar 2011-Mar 2013	Social Housing	England	Before 1919 Victorian End-Terrace	1	Gas-Scenario B	*64*	*30*	*-76*	*76*	*48*
					1992 Mid-Terrace	1	Gas-Scenario B	*41*	*-66*	*25*	*62*	*57*

[80]	Energy Bills. No energy usage pre-retrofit for Munich apartments	2014-2015	Social housing apartments	Ulm and Munich, Germany	Apartments	177 in Ulm and 31 in Munich	Scenario A	*8*	*-17*	*7*	*17*	*18*

Note

*For the EPG, ESD and RE results, figures shown in bold are calculation method used in study and figures shown in italic are estimated from graphs or other information provided in study.

Abbreviations

DH: District Heating
DHW: Domestic Hot Water
DT: Detached
EL: Electricity
ETR: End-Terrace
LT: Lighting
PRE: Pre-Retrofit

POST: Post-Retrofit
Scenario A: SH
Scenario B: SH and DHW
Scenario C: SH, VT, Pumps and fans for SH and VT, DHW and LT
Scenario D: All end uses excluding SH, DHW and plug loads

SC: Solar Collectors
SH: Space Heating
TAS: Thermal Analysis Software
TM: Temperature
TR: Terraced
VT: Ventilation
WM: Warm Water Solar Collector Units

found depending on the percentage of heat assumed to be accounted for by the secondary heating system pre-retrofit.

The models used in all the reviewed quasi-experimental studies in Table 2.5 ([45], [46], [55], [47]–[54]) and in several of the reviewed econometric studies of Table 2.4 ([132]–[134], [137], [141]) relied upon steady state/quasi-steady state models/formulae to determine the theoretical space heating demand of a building. These models/formulae are representative of the formulae used for producing an ENPC.

Of the reviewed quasi-experimental studies involving the use of steady state/quasi-steady state models/formulae, identified reasons for the discrepancies in actual energy usage to theoretical energy usage of engineering energy demand models can be categorised as material and technology performance characteristics, malfunctioning technology and energy demand practices. Regarding material and technology performance characteristics, studies have highlighted the inaccuracy of the energy audit [148], energy model [46], space heating system efficiency [54], building air-tightness [53], [149], building fabric characteristics [53]–[55] and solar coefficient [54] as reasons for the discrepancies in actual energy usage to theoretical energy usage of engineering energy demand models. In addition, malfunctioning space and water heating equipment [50], [53], [147] have also been identified. Furthermore, energy demand practices such as internal room temperatures [47], [50], [80], heating duration [150], space heating set point temperatures [54], [56], [150], multiple space heating systems contributions to the heating load [47], [147], hot water heating practices [50], [56], [151], space heating return temperature, ventilation practices [80] and occupancy patterns [80], [152] have been identified as reasons for the discrepancies in actual energy usage to theoretical energy usage of engineering energy demand models.

A lack of social dimensions in energy research [153], [154] has led to calls for it to be utilised to help in understanding the gap that presently exists between the expected and real energy demand practices of building occupants installing energy efficiency retrofit measures [155], [156] and to examine the social impacts from a building energy efficiency retrofit [154].

2.3.2 Life Cycle Energy Efficiency Retrofit Studies

In a review of LCA energy efficiency retrofit studies, Vilches et al. [154] noted a lack of studies that focused on environmental, economic and social impacts resulting from building energy retrofits. Social indicators have been used in multiple studies to assess the sustainability of the electricity network [157], [158], waste treatment and management [159], industrial applications [159], energy related applications [159], photovoltaic systems [160], hybrid renewable energy systems [161], treatment of end of life automotive glass [162] and treatment of landfill sites [163]. Social indicators representing a local consumer, local community, worker or society can be used to assess the social impact of a project [164].

For building retrofits, indirect householder and societal social benefits outside the direct energy, carbon emissions and cost savings have been used [165]. Studies on the links between energy efficiency retrofits and improvements of householders quality of life, well-being, mental and physical health and use of the of health service have been conducted [166], [167].

Published energy efficiency retrofit case studies using life cycle indicators are summarised in Table 2.6. The case studies are summarised in terms of their (i) location, (ii) building type, (iii) energy performance design target, (iv) evaluation indicators, (v) applied retrofit energy efficiency measures, (vi) whether the case studies operational energy consumption is simulated with a software tool and (vii) whether the assessment method used for evaluating a retrofit design incorporated the cost optimal methodology. The evaluation indicators are categorised as environmental, economic or social indicators. Studies had to include indicators for two of the three categorises to be included in Table 2.6.

Several studies have used LCA indicators to evaluate retrofitting/refurbishing case studies [154], [168], [177]–[179], [169]–[176]. Two studies on residential buildings in Ireland evaluated the environmental impact of retrofitting buildings to various Irish building regulations, as well as passive energy performance standards [175], [176]. Famuyibo et al. [176] found Irish semi-detached housing units retrofitted to the same energy performance levels had different life cycle GWP impacts.

Thiers & Peuportier [177] examined the environmental life cycle impact of retrofitting passive house and multi-family social housing building to net-zero source energy building using 12 environmental indicators. The authors discovered no specific heating system solution was the optimum choice for all of the 12 environmental indicators evaluated.

Numerous studies have applied a cost-optimal approach to minimum energy performance methodology to assess cost-optimal retrofit solutions for the building stock of several countries. Studies on single family houses [180], [181] and multi-family/apartment buildings [180], [182]–[185] have been conducted on Italian [180], [181], Portuguese [182], [183], Swedish [185] and Turkish [184] building stock. Several sensitivity parameters effecting the cost-optimal results have been examined including discount rates [182], [183], [185], energy prices [182], insulation thicknesses [185], building orientation [183], building age [180] and building lifespan [180]. Other studies incorporated environmental life cycle assessment in their assessment methodology, along with the cost-optimal approach [186]–[193].

Of the 25 studies included in Table 2.6, only six evaluated social indicators. In Table 2.6, thermal comfort is grouped under the social category even though studies may not have explicitly considered it a social indicator. Chantrelle et al. [186] evaluated the percentage of people dissatisfied with thermal comfort as one of the initial criteria in their multi-stage optimization process for developing retrofit package solutions for buildings. Risholt et al. [172] used improved thermal comfort, improved air quality, improved aesthetics, self-involvement and major/stepwise social indicators as part of their methodology for assessing the sustainability of a building retrofit. Holopainen et al. [171] illustrated some of the results collected as part of the NeZeR [194] project which assessed the technical feasibility and social feasibility of energy efficiency retrofit technology on a scale of 1-5. Neroutsou & Croxford [173] examined two energy efficiency retrofit designs for overheating potential in the main living room based on the hottest day of a weather file.

Almeida et al. [189] presented some findings from the International Energy Agency (IEA) Energy in Buildings and Communities Annex 56 project [165]. This project developed a methodology justifying selecting retrofit energy efficiency solutions which achieve energy savings beyond the cost-optimal. The methodology developed a matrix of co-benefits expected from retrofit energy efficiency measures. The benefits were based on the positive and negative experiences and perceptions of building users from a number of case study buildings. Touceda et al. [156] assessed the impact of an energy efficiency retrofit on the health of workers and householders, economic growth, employment and alleviation of fuel poverty using a Belgian house case study.

As illustrated in Table 2.6, only two studies incorporate life cycle environmental, life cycle cost and social indicators [165], [171], [189]. However, the studies assessed a limited number of life cycle environmental indicators (life cycle GWP, life cycle CED, life cycle CEDnrp). Furthermore, there are limited studies whose results are based on monitored data [156], [173], [195], [196] despite building energy efficiency retrofits not experiencing estimated energy savings as highlighted in Section 2.3.1. None of the four studies using monitored data evaluated their respective case studies using environmental, economic and social indicators based on monitored data [156], [173], [195], [196]. In studies that have monitored data, either (i) the research study is based on a small sample of buildings, (ii) only one phase of the retrofit was monitored, (iii) part of the monitored data was used in the assessment or (iv) the monitored data was used to validate an energy performance model upon which the findings were made.

Thus, for building retrofits, inaccurate assumptions regarding material and technology performance characteristics and energy demand practices of people have been identified for the discrepancies in expected retrofit energy savings. To examine whether social impacts need to start being quantified with economic and environmental indicators in designing and evaluating the sustainability of a residential building energy efficiency retrofit in Ireland, building thermal fabric and heating system retrofit energy efficiency design packages for residential buildings in Ireland are examined in **Chapter 4** incorporating environmental, economic and social indicators. Furthermore, this research will help address the limited number of life cycle retrofit studies incorporating environmental, economic and social indicators.

Table 2.6: Summary of retrofit studies with LCC and operational energy demand as minimum indicators

Ref.	Country	Building Type			Design Target	Assessment Criteria			REEM			SIM	CO
		SF	MF	Non-Res		Environmental	Economic	Social	FB	HS	RN		
[197]	SL		x		U-values reaching 2012, 2016 and 2021 requirements		LCC		x			Unknown	
[195]	SW		x	x	Light retrofitting: high impact to energy demand; advanced-high and low energy demand reduction	OE	LCC, cost effective ranking					Base model verified with monitored data	
[181]	IT	x			nZEB	OE	LCC		x	x	x	x	x
[198]	IT		x		Cost-optimal	OE	LCC	Thermal comfort	x	x		x	
[182]	PR		x		Zero energy building and cost-optimal	OE	LCC		x	x	x	x	x
[183]	PR	x	x		Nearly zero energy retrofit	OE	LCC		x	x	x	x	x
[199]	IT		x		Not specified	OE	LCC		x	x		x	x
[200]	FL		x		nZEB apartment renovation	OE	LCC		x	x	x	x	x
[201]	IT	x			UNK	OE	LCC		x	x		x	
[180]	IT	x	x		UNK	OE	LCC		x	x	x	x	x
[184]	TY		x		UNK	OE	LCC		x	x	x	x	x
[185]	SW		x		UNK	OE	LCC		x			x	x
[196]	CH		x			OE	NPV, IRR, payback		x	x			
[202]	REU	x	x		No energy target specified	LC GWP	NPV and IRR		x				

[186]	FR			x	N/A	OE, LC CO_2	Investment Cost	Thermal Comfort	x			x		x
[172]	NR	x			nZEB	OE and CO_2 savings	LCC	Thermal Comfort, Air Quality, Aesthetic Improvements	x	x	x	x		
[187]	PR	x			Not specified	LC CC, LC HT, LC AT, LC TT, LC EP, LC AP	LCC		x	x	x			x
[188]	PR	x				LC NRPE, LC GHG, OE	LCC		x	x		x		x
[171]	FL, NTH, RM, SP, SW		x		Traditional and nZEB	LC GHG, OE	LCC	Technical and social based on risk factor of 1-5	x	x	x	x		
[173]	UK	x			Part L1 B and passive house refurbishment	Energy/Carbon payback	LCC	Thermal comfort	x			x		
[174]	PL	x		x	Not specified	LC CEDnrp, LC CC, LC ODP, LC TA, LC FE	LCC, EAC		x		x	x		
[192]	FD		x		nZEB apartment renovation	OE, LC CO_2	LCC		x	x	x	x		x
[165], [189]	AU, DK, SW, CZR, PR, SP	x	x	x	nZEB renovation	LC GWP, LC CED, LC CED_{nr}	LCC		x	x	x			x
[156]	BG	x			Very low energy retrofit	LC CC, LC ODP, LC PM		Human health, employment, contribution to growth, fuel costs and house affordability	x	x	x	x and monitored data		
[190]	SP		x		BAU, retrofit-requirement, new build requirements, passive requirements	LC ADP, LC AP, LC EP, LC GWP, LC ODP, LC POCP	LCC		x			x		x
Abbreviations														

AU: Austria
BG: Belgium
CH: China
CO: Cost-Optimal Method Employed
CZR: Czech Republic
DK: Denmark
FB: Fabric
FL: Finland
FR: France
HS: Heating System
IT: Italy
LC AP: Life Cycle Acidification
LC AT: Life Cycle Aquatic Toxicity
LC CC: Life Cycle Climate Change
LC CO_2: Life Cycle CO_2
LC EN: Life Cycle Energy
LC EP: Life Cycle Eutrophication
LC CED: Life Cycle Cumulative Energy Demand
LC CED_{nrp}: Life Cycle Cumulative Energy Demand Non-Renewable
LC FE: Life Cycle Freshwater Eutrophication
LC GHG: Life Cycle Green House Gas Emissions
LC GWP: Life Cycle Global Warming Potential
LC HT: Life Cycle Human Toxicity
LC NRPE: Life Cycle Non-Renewable Primary Energy
LC ODP: Life Cycle Ozone Depletion,
LC PM: Life Cycle Particulate Matter Formation
LC TT: Life Cycle Terrestrial Toxicity
MF: Multi-Family Building
NON-Res: Non-Residential Building
NR: Norway
NTH: Netherlands
PRT: Portugal
REEM: Retrofit Energy Efficiency Measure
REU: Representative of EU
RM: Romania
RN: Renewable Technology
SF: Single Family Building
SIM: Simulated Data
SL: Slovakia
SP: Spain
SW: Sweden
TY: Turkey

2.4 Understanding the Energy Use of People-The Concept of Energy Cultures

As noted at the end of Section 2.3.1, a lack of social dimensions in energy research [153], [154] has led to calls for social scientific energy research capable of addressing the gap that presently exists between the expected and actual energy use of building occupants installing energy efficiency retrofit measures [155], [156]. While the social impacts from a building energy retrofit can justify not achieving expected energy savings or retrofitting to a greater energy efficiency standard, it is necessary to understand how and why people use energy within a building to be able to predict environmental and social impacts from a change in a building's technical characteristics. That said, buildings are complex socio-technical systems [203]. Building energy use is affected by the interrelationships between physical performance of the fabric, building systems, the occupants' understanding of the building systems, expectations and perception of comfort and occupants habitual behaviours [204]. For example, Byrne et al. [205] found Irish residential building occupants desire for an improved thermal comfort level resulted in energy savings being notably less than the potential energy savings from a building energy efficiency retrofit.

To help understand the energy use of people in buildings, social-scientific research on the cultural dimensions of domestic energy use has gained momentum of late [206]–[208], following some initial pioneering work [209]–[211]. This growing body of work includes anthropological, sociological and interdisciplinary studies of activities that are inextricably linked to household energy use (e.g. eating and cooking, mobility). Many of the studies feature detailed qualitative inquiries into the quality and composition of these domestic activities.

A considerable number social-scientific and interdisciplinary energy studies have deployed the concept of energy cultures to integrate social, cultural and material factors into the analysis of domestic energy use and its transformation [206], [207], [210]–[213]. While these vary in terms of focus and priorities (e.g. individual behaviour versus collectively shared practices; personal attitudes versus socially negotiated norms), they all move beyond existing technocentric work that views energy use as largely determined by physical and material conditions and that ignores the central role of people's habits and routines in shaping energy demand in the home. These views are held despite findings of habits and routines co-evolving with changes to the physical infrastructure of buildings [214], [215].

In this context, the concept of energy cultures has emerged as a framework or heuristic for investigating domestic energy use across different scales and social groupings [206], [207], [216]. It combines an emphasis on social and cultural norms and actual energy use with a focus on prevailing material conditions, fusing elements from a range of culture-sensitive approaches to the study of energy use.

The energy cultures framework (ECF) treats energy use as collectively shared and culturally mediated while also recognising its contingency upon factors relating to both material systems and individuals' characteristics and activities (e.g. behaviour intentions guided by internalised norms). Originally developed for multidisciplinary research on energy behaviour [207], including reasons for the (in)effectiveness of state-led efforts to increase consumer energy efficiency, the ECF has also proved its worth in inquiries into the dynamics of energy use at different scales (e.g. local, regional, national and international). For example, the EU-H2020-funded ENERGISE project, a multidisciplinary effort to understand and potentially transform domestic energy use, uses an innovative conceptual framework that fuses energy cultures thinking with insights from practice theory and that introduces the linking concept of 'practice cultures' [217].

The field of energy cultures research displays significant theoretical and conceptual divergences. For example, vast variations exist in how the role of individuals and their capacity to bring about change are viewed and portrayed. Here, approaches that prioritise individuals' behaviour contrast (and sometimes clash) with practice-oriented views that treat individuals largely as 'practitioners' or 'carriers of practices' [218]; refer to [213] for a discussion of these tensions. On the practice-theoretical side, many authors have criticised the persistent dominance of approaches that overemphasise the role of the individual in energy consumption. For example, Shove [219] call for a move 'beyond the ABC', that is, the dominant model of human behaviour that assumes a linear connection between attitude (A), behaviour (B) and choice (C). Similarly, Spurling et al. [220] argued that ‘social practices are a better target of intervention for sustainability policy than ‘behaviour’, ‘choice’ or technical innovation alone’.

In contrast, ECF advocates have been less concerned with a shift in attention away from individual behaviour. Instead, they have developed ‘a structure for addressing the problem of multiple interpretations of ‘behaviour’ by suggesting that it is influenced by the interactions between cognitive norms, energy practices and material culture’ [206]. This difference in focus on individuals and practices respectively is perhaps the most significant source of tension within the energy cultures debate (see [208], [219]–[221]). This said, this tension remains largely unresolved, with different approaches co-existing.

Different variants of energy cultures thinking also diverge in their view of how practices become entrenched and hard to change and what causes this inherent ‘stickiness’ [222]. Some ascribe the longevity of particular practices to individuals’ hard-to-shift habits and routines but emphasise possibilities for transformation through behaviour change. For example, responding to the observable persistence of daily routines and habits and related patterns of energy use in the face of change initiatives, Stephenson et al. [206] presented the ECF as a tool to assist in understanding the factors that influence energy consumption behaviour, and to help identify opportunities for behaviour change. In contrast, many practice-theoretical approaches recognise the significance of entrenched structures, including prevailing systems of provision and established (sets of interlocking) practices [220] in shaping actual and potential change trajectories.

Overall, these divergent, yet complimentary strands of thinking about energy cultures, that is, particular combinations of individuals’ (routine) actions and socio-technical settings within which these occur, have produced important socio-scientific insights into the nature and dynamics of domestic energy use, albeit with different foci. The decision to use the ECF to conceptually frame the empirical material presented in **Chapter 5** was primarily informed by epistemological and methodical considerations. Given the history of the ECF as a heuristic tool for structuring multidisciplinary, multi-method research on energy use, it was deemed to be particularly suitable for the research presented.

2.4.1 Using the ECF to investigate energy retrofitting

As outlined above, this research draws directly on the ECF developed by Stephenson et al. [206], [223] and further elaborated in [208]. It distinguishes between three key elements that contribute to the formation of distinct energy cultures: 1) prevailing material cultures (e.g. technologies, energy infrastructure), 2) attitudes, perceptions and social shared norms regarding energy use (e.g. whether wasting energy is seen as acceptable in society, expectations regarding thermal comfort), and 3) actual practices that make up everyday life such as heating and cooling, cooking, or washing, and that all involve the (direct or indirect) use of energy (see inner circle in Figure 2.1).

Energy cultures interact with contextual factors and influences (Figure 2.1). As Stephenson et al. [206] emphasise, 'wider influences are not exogenous to the energy culture, but exert influence and are in turn influenced by it — for example, law and policy are affected by values, aspirations, beliefs and understandings, and in turn affect them' (p. 6124). The dashed circle in Figure 2.1 suggests a high level of permeability between the three energy culture elements and the wider context. Importantly, these systemic influences might pertain to dynamic social phenomena such as energy policy and regulation (e.g. efficiency rating schemes, building regulations) or demographic conditions (e.g. the rise in the number of single households).

The ECF has been used to understand how cultural formations result in sustainable outcomes that are of interest [208]. The ECF has been applied to a number of studies revolving around residential buildings including understanding the challenges of living in fuel poverty [224], the energy cultures of the elderly which are driving energy consumption [225] and comparing the impact of home audits and community events resulting in a change in householders energy cultures [226]. In Stephenson's examination of how the ECF has been applied in research to date [208], the author provides areas of exploration of where the ECF can be used. One area includes examining how aspects of an actors' culture and the sustainability-related outcomes are affected if one aspect of the actors' culture changes. Another area includes examining how changing or unchanging sustainability outcomes are due to aspects of an actors' culture.

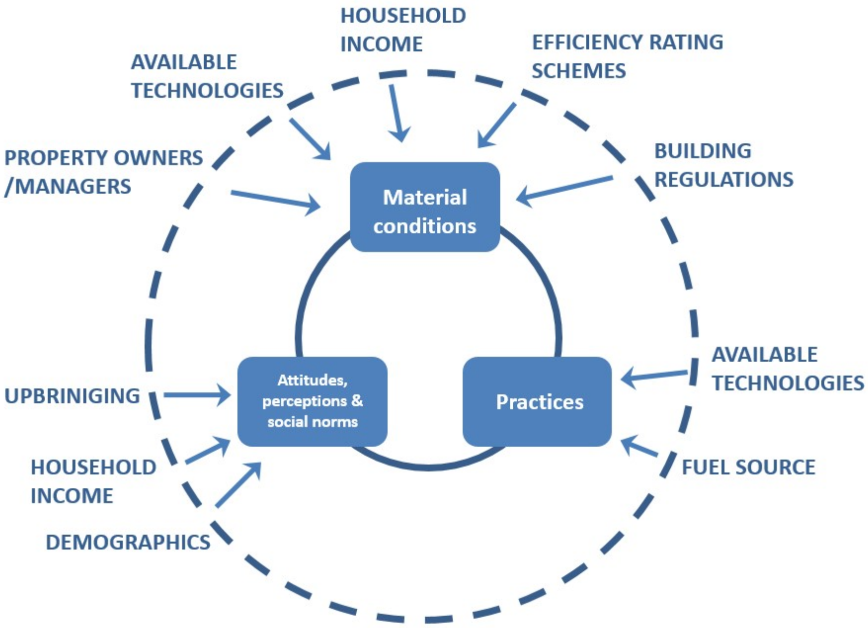


Figure 2.1: Energy culture: Key elements and systemic influences (adapted from Stephenson et al. [206]*)*

Table 2.7: Three Elements of Energy Cultures.

Element	**Examples of indicators**
Material conditions	Dwelling characteristics, insulation, energy sources, heating devices, number of appliances
Attitudes, perceptions and social norms	Aspirations, expected comfort levels, environmental concern, respect for tradition
Practices	Number of rooms heated, heat settings, hours of heating, ventilation practices, use of appliances, maintenance of technologies

Source: Authors' extension of Stephenson et al. [206], [223]

In **Chapter 5,** a careful operationalisation of the three constitutive elements of energy culture (Table 2.7) made it possible to empirically investigate (i) the impact energy efficiency retrofitting has on energy cultures and the sustainable related outcomes (building energy use and the internal environment) among inhabitants of urban co-operative social housing units in Ireland and (ii) examine possible relationships between energy efficiency retrofitting, domestic energy use practices, material conditions and the attitudes, perceptions and social norms of householders with regards to the sustainable related outcomes.

2.5 Changing Energy Usage Behaviours and Habits Using Energy Consumption Feedback

With people playing a key role in how energy is used within buildings, energy consumption feedback to householders has been deployed as a mitigation measure to reduce the impact people have on the energy consumption of buildings. Research into the effect of providing energy consumption feedback to energy consumers has become more prevalent since the mid-2000s [227], [228] after a surge in interest in the late 1970s due to the energy crisis [228]. Feedback can be both direct and indirect with each feedback form having varying impacts. Direct energy feedback is instantaneous information on the energy consumption of a building. This is often provided through an in-house display (IHD), a webpage, plug meters, thermostats, manually reading meters or ambient devices [229]. Indirect energy feedback is processed information that is often provided through billing, e-mail, SMS, energy reports or webpages. Direct and indirect energy consumption feedback can be represented as aggregate (overall) building energy use or disaggregated into end uses (space heating, appliances, etc.). Direct feedback is considered to be more effective for electricity energy consumption [229]–[233], while indirect feedback is more effective for heating energy consumption [230]. Studies have found the range of savings associated with energy consumption feedback to range from 2% to 20% [232]–[237], although some studies report the range to be from -8.2% to 55% savings depending on the quality of the study [227], [230].

The deployment of smart meters is seen as an energy saving measure for the Irish building sector [44]. Trial studies on the effectiveness of installing electricity [238] and gas [239] smart meters have been conducted on Irish housing. Both studies, managed by the Commission for Energy Regulation, compared the effects of providing four different feedback formats to control groups. The energy consumption feedback reduced, on average, householder's electricity consumption by 2.5% and gas consumption by 2.9%, respectively. The effectiveness of the feedback formats ranged from 1.1% to 3.2% savings for the electricity consumers with those receiving feedback via a bi-monthly bill energy usage statement and electricity monitor achieving the highest savings. Each group however received varying price tariffs for their electricity consumption. Gas consumers receiving a bi-monthly bill, energy usage statement and an IHD experienced the highest savings in the gas trial. Although this group was the only to receive a variable price tariff.

Many government initiated retrofit programmes, including Ireland's, focus on retrofitting building technical systems as energy efficiency measures, while behavioural changes are generally neglected [44], [78]. It is believed that technical interventions on a building are more expensive to carry out in isolation without the cooperation of the building occupants [79] and an accompanying programme designed to encourage energy consumption behaviour change [234]. Energy consumption feedback is often used to encourage energy consumption behaviour change.

Only three energy consumption feedback studies, best to the authors' knowledge, examined the impact of energy consumption reduction in households which employed both technical energy efficiency measures on a building and an accompanying programme designed to encourage energy consumption behaviour change [78], [240], [241]. 25 low-income households in Cyprus were involved in an energy consumption feedback study with 14 households receiving energy consumption feedback and 11 households installing a photovoltaic system in addition to receiving energy consumption feedback [78]. The households who had a photovoltaic system installed reduced their electricity consumption by 36%, compared to a 27% reduction experienced by the 14 households who only received energy consumption feedback.

The James & Ambrose [240] study included 320 low-income Australian households involved in an energy efficiency programme. The households were divided among four groups: (i) houses which received one or more of eleven different energy efficiency retrofit measures, (ii) houses which received one or more of five different behaviour change measures, (iii) houses which received both energy efficiency retrofit and behaviour change measures and (iv) a control group [240]. Combined energy efficiency retrofit, and behaviour change measures were found to be more effective for gas consumers and combined energy (electricity and gas) consumers rather than being carried out in isolation. However, energy efficiency retrofit, and behaviour change measures were more effective when carried out in isolation for electricity consumers. No electricity consumption group experienced statistically significant savings. The ineffectiveness of behaviour change measures for reducing electricity consumption is similar to findings of other studies on electricity consumption feedback for low-income housing [242], [243].

63 households involved in low carbon community activities received either technical and/or behavioural interventions. As the physical building characteristics, technical retrofit and behavioural intervention varied amongst the sample of monitored houses, it was not possible to differentiate between the effectiveness of the technical retrofit and the behavioural intervention [241].

Despite the high number of Irish schemes available for securing energy efficiency retrofit grants, no Irish study has been carried out to examine the impact energy consumption feedback has in combination with a technocentric energy efficiency retrofit. An energy saving initiative (ESI) was implemented, as detailed in **Chapter 6,** with the purpose of providing householders with the skills and knowledge on how to reduce and or change their energy consumption without compromising the health and comfort of the building occupants. The study was carried out to assess whether the energy consumption feedback would elicit a change in the energy demand practices of the householder and in turn change their energy consumption levels. The ESI focused on four energy consumption end use areas: (i) space heating (SH) services, (ii) domestic hot water (DHW) heating services, (iii) domestic appliance services and (iv) cooking services; (i) and (ii) were provided primarily through gas energy consumption, while (iii) and (iv) were provided primarily through electricity energy consumption.

2.6 Conclusions

Energy efficiency policies to mitigate the environmental impact of buildings have been categorised as new building constructions, building retrofits, efficiency of building equipment and the energy consumption behaviour of building occupants [14]. With regards to new build, building retrofits and the energy consumption behaviour of building occupants, some key research gaps in these three areas, in an Irish context, are identified as part of the literature review which are tackled in this thesis. This is carried out by examining the interrelationships between the operational energy demand practices in buildings, the people occupying the buildings and the materials and technology used in the construction/retrofit of the buildings. The interrelationships between the operational energy demand practices in buildings, the people occupying the buildings and the materials and technology used in the construction/retrofit of the buildings are examined through the lens of the cost-optimal methodology framework, life cycle analysis and a mixed method approach.

With LCA mandatory in building design in several EU countries [41], a lack of LCA studies in relation to Irish residential buildings and a large range of environmental impacts for buildings designed to high energy performance standards, a standardised comprehensive environmental LCA examining the life cycle breakdown and more accurate environmental intensity values from an Irish context is necessary. In **Chapter 3**, the interrelationship between the materials and technology used in the construction of new buildings and the operational energy demand is the primary focus. A life cycle assessment study, incorporating multiple environmental and economic indicators, on Irish residential building stock built to past and present building energy performance standards is addressed.

For building retrofits, inaccurate assumptions regarding material and technology performance characteristics and energy demand practices of people have been identified for the discrepancies in expected retrofit energy savings. To examine whether social impacts need to start being quantified with economic and environmental indicators in designing and evaluating the sustainability of a residential building energy efficiency retrofit in Ireland, building thermal fabric and heating system retrofit energy efficiency design packages for residential buildings in Ireland are examined in **Chapter 4** incorporating environmental, economic and social indicators. **Chapter 4** links the social impact people occupying residential houses experience from a change in the materials used for retrofitting their houses and their energy demand practices in addition to addressing the limited number of life cycle retrofit studies incorporating environmental, economic and social indicators.

While the social impacts from a building energy retrofit can help justify not achieving expected energy savings or retrofitting to a greater energy efficiency standard, it is necessary to understand how and why people use energy within a building to be able to predict environmental and social impacts from a change in a building's technical characteristics. **Chapter 5** uses the concept of energy cultures to aid in understanding how changing building materials via a technocentric energy efficiency building retrofit impacts operational energy demand practices, people, energy consumption and energy savings of co-operative social housing residential buildings in Ireland .

With people playing a key role in how energy is used within buildings, energy consumption feedback to householders has been deployed as a mitigation measure to reduce the impact people have on the energy consumption of buildings. An energy saving initiative (ESI) was implemented, as detailed in **Chapter 6,** with the purpose of providing householders with the skills and knowledge on how to change their energy consumption without compromising the health and comfort of the building occupants. The study was carried out to assess whether the energy consumption feedback would elicit a change in the energy demand practices of the householder and in turn change their energy consumption levels. Reasons relating to the operational energy demand practices in buildings, the people occupying the buildings and the materials used in the construction/retrofit of the buildings are identified for the (in)effectiveness of the energy consumption feedback.

Chapter 3. Life Cycle Analysis of New Build Residential Buildings

3.1 Introduction

EU policy has required EU countries to improve the energy efficiency of their respective building energy performance standards and is now requiring EU countries to move towards nZEB buildings energy performance standards. With LCA mandatory in building design in several EU countries [41], a lack of LCA studies in relation to Irish residential buildings and a large range of environmental impacts for buildings designed to high energy performance standards, a standardised comprehensive environmental LCA examining the life cycle breakdown and more accurate environmental intensity values from an Irish context is necessary. This chapter examines from an Irish context how changes from past to present building regulations for new buildings are impacting the building's material and technology and energy use from an environmental and economic perspective. The parameters employed in Chapter 3 to examine the interrelationships between the operational energy demand practices in buildings, the people occupying buildings and the materials and technology used in new buildings are depicted in Figure 3.1.

The chapter is divided into four sections. Section 3.2 describes how the life cycle environmental and economic impacts of the case study buildings are determined. Furthermore, the procedure for calculating the cost-optimal levels of minimum energy performance case study designs, the weighting framework for calculating the combined impact of the life cycle indicators for the case study designs and the sensitivity analysis on the impact of time value of money, future energy prices and future electricity generation fuel mix are presented. Section 3.3 introduces the theoretical south orientated semi-detached residential two storey masonry building that the results are based on. In Section 3.4, the environmental and economic impact of the case study buildings designed to past and present building regulations for new buildings are presented. Finally, Section 3.5 discusses the impact changes in Irish building regulations are having based on the assessed criteria and the areas that new building design strategies should focus on as Ireland moves to a decarbonised economy 2050 are also assessed.

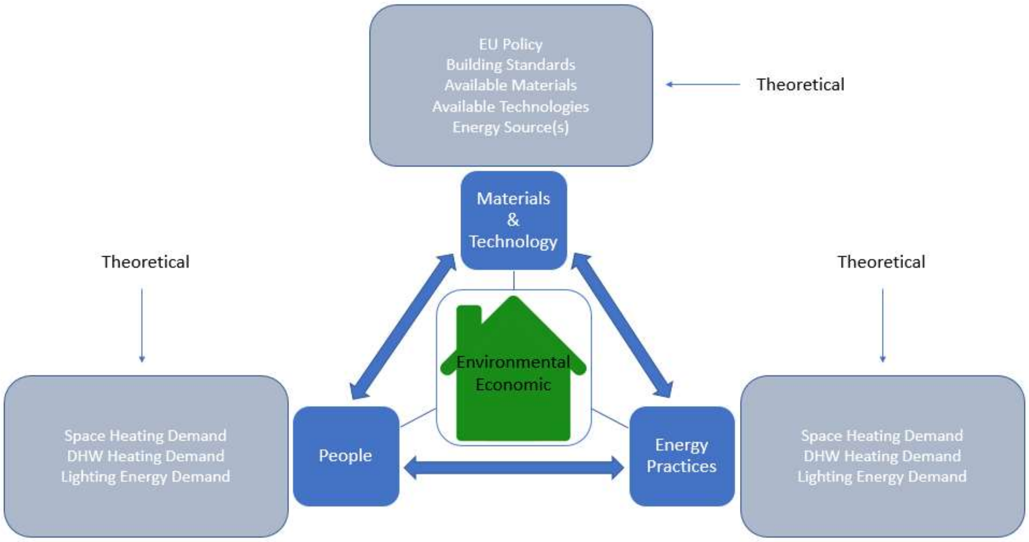


Figure 3.1: The parameters employed in Chapter 3 to examine how the interrelationships between the operational energy demand practices in buildings, the people occupying buildings and the materials and technology used in new buildings influence the environmental and economic impact of residential buildings in Ireland moving towards nZEB standards.

3.2 Methodology

Utilising a standardised comprehensive LCA approach [244], [245], an environmental and economic LCA is conducted on various building designs, stressing the impact of different design strategies over an entire building's life cycle. The life cycle stages evaluated are expressed according to the modularity principle of a building life cycle [246].

3.2.1 Material Production Stage (Module A1-A3)

The embodied environmental impact during the material production stage of all materials/components (excluding appliances, fixtures and fittings) in the construction of the case study buildings are assessed using the Inventory for Carbon and Energy (ICE) V.2.0 [109]. This stage is also known as a cradle to gate system boundary.

The embodied environmental impact caused by extracting, processing and manufacturing of materials can be expressed mathematically as by any of the equations 3.1 to 3.4 depending on the data available:

$$E_{m,n} = \sum_{1}^{h} V_i \rho_i EKG_{m,i} \tag{3.1}$$

$$E_{m,n} = \sum_{1}^{h} V_i EV_{m,i} \tag{3.2}$$

$$E_{m,n} = \sum_{1}^{h} A_i EA_{m,i} \tag{3.3}$$

$$E_{m,n} = \sum_{1}^{h} L_i EL_{m,i} \tag{3.4}$$

where $E_{m,n}$ is the embodied environmental impact of indicator m for case study n. The embodied intensity for material i of indicator m can be given in terms per kg ($EKG_{m,i}$), per m^3 ($EV_{m,i}$), per m^2 ($EA_{m,i}$) or per m ($EL_{m,i}$). ρ_i is the density (kg/m^3), V_i is the volume (m^3), A_i is the area (m^2) and L_i is length (m) of material i.

If embodied intensities for materials are unobtainable from the ICE database [109], data is sourced from other available databases and literature. A breakdown of the embodied intensities of the materials used for the construction of the case study buildings and their source is given in Appendix B.

3.2.2 Use Stage: Building Operation (Module B6)

The annual secondary energy required to operate the case study buildings is estimated using DEAP [25]. A life cycle of 60 years is taken as the life span of a residential building in Ireland. DEAP accounts for the energy required for (i) lighting, (ii) ventilation, (iii) space heating and (iv) domestic water heating. Despite the inaccuracy of standard assessment procedures for estimating energy demand as highlighted in Section 2.3, standard assessment procedures have been found to be more accurate for residential buildings with high energy efficiencies [148]. As such, the nZEB case study designs in this analysis are assumed to be accurate. The operational environmental impact from the case study buildings can be expressed mathematically as:

$$O_{m,n} = \sum_{x=1}^{y} \left[\sum_{j=1} OI_{m,j,x} \, DE_j \right] \tag{3.5}$$

where $OI_{m,j,x}$ (indicator m/MJ$_{del}$) is the primary energy conversion factor of fuel type j for indicator m in year x of the building lifespan y and DE_j (MJ$_{del}$/m^2/yr) is the delivered energy per heated floor area per year of fuel type j. Using the total values of $E_{m,n}$ and $O_{m,n}$, the life cycle environmental impact of indicator m for case study n is evaluated.

3.2.3 Net Construction Costs

The Spon Construction Price Book [247] is utilised for the economic evaluation of the net construction cost (NCC) of the components in the case study buildings. The NCC accounts for the labour, plant and material economic costs of the components in the case study buildings. Economic construction costs are updated to current values using relevant consumer price indices [248] and do not include Value Added Tax (VAT). If economic construction values are unobtainable from the Spon's Construction Price Book [247], data is sourced from other available databases and literature, as noted in the relevant sections of the thesis.

3.2.4 Operational Economic Costs

Using the delivered energy of the respective fuels to each of the case study buildings and current Irish residential energy prices [249], operational costs of the case study buildings are determined excluding VAT. Standing charges, which are a combination of the fixed charges associated with providing electricity and gas network services and a share of the supply costs in servicing a costumer's account, are not included in the estimation of operational energy costs. These charges are applied at a fixed rate per day to a customer's account.

3.2.5 Cost-Optimal Methodology Framework

The cost-optimal methodology framework for calculating cost optimal levels of minimum energy performance requirements for buildings and building elements [16] is used to determine the cost-optimal design solution. However, the embodied energy of the materials invested into a building is accounted for despite not being required as part of the cost-optimal methodology framework set out by the EPBD. The life cycle cost (LCC) part of the cost-optimal methodology framework for case study n can be expressed mathematically as:

$$LCC_n = NCC + \sum_j \left[\sum_{x=1}^{y} (OEC_{j,x} Rd_x + Cc_{j,x}) - Vf_{j,y} \right] \tag{3.6}$$

where NCC is the net construction cost or initial investment costs (€), $OEC_{j,x}$ is the operational economic cost during year x for heating system j, $Cc_{j,x}$ is the carbon cost during year x for heating system j based on the sum of the annual OC emissions, $Vf_{j,y}$ is the residual value of heating system j at the end of the building lifespan y and Rd_x which is the discount factor for year x based on discount rate r which is determined using:

$$Rd_x = \left(\frac{1}{1 + r/100} \right)^x \tag{3.7}$$

where x is the number of years from the starting period and r means the real discount rate.

The LCC can be used from a customer/householder perspective and from a macroeconomic/societal perspective. From a householder perspective, all grant subsidies and applicable taxes including VAT and charges should be taken into account and the cost of carbon should be excluded [75].

When examining the LCC from a macroeconomic/societal perspective, all grant subsidies and applicable taxes including VAT and charges should be excluded and a the cost of carbon should be included [75].

3.2.6 Sustainability Index Factor

The cost-optimal methodology framework for calculating cost optimal levels of the minimum energy performance only considers two indicators; energy and cost. Numerous tools have been developed, and are in operation across Europe, that use multiple indicators to evaluate the sustainability of a building, such as the Home Quality Mark (HQM) [250], DNGB Certificate System [251], Leading the Environment for Sustainable Construction (LiderA) [251], Sustainability Assessment Tool (SBTool) [251], the High Quality Environmental Standard (HQE) [251] and the Home Performance Index (HPI) [252]. Each tool has varying types of indicators. Each of the tools' indicators can be grouped under, what are commonly considered, the three pillars of sustainability: environment, social and economic. Other research has used the three pillars of sustainability to rank how green a material is (see, for example, [253]).

In this chapter, it is examined whether there is a need to start moving away from using the cost optimal energy performance method, which incorporates only energy and cost as indicators, to a method that incorporates the aforementioned three pillars of sustainability. The methodology used is termed the Sustainability Index Factor (SIF) and can be expressed mathematically for case study *n* as:

$$SIF_n = \frac{aECO_n + bSOC_n + cE \quad _n}{k} \tag{3.8}$$

where a, b and c are weighting factors for each of the respective categories; k is $\Sigma(a,b,c)$; ECO_n is the economic impact of case study n; SOC_n is the social impact of case study n; and ENV_n is the environmental impact of case study n and can be expressed mathematically as:

$$ECO_n = \sum_{m=1}^{q} \left[\left(\frac{eco_{m,n}}{\left(\frac{\sum_{n=1}^{p} eco_{m,n}}{p} \right)} \right) w_m \right] \tag{3.9}$$

$$SOC_n = \sum_{m=1}^{q} \left[\left(\frac{soc_{m,n}}{\left(\frac{\sum_{n=1}^{p} soc_{m,n}}{p} \right)} \right) w_m \right] \tag{3.10}$$

$$ENV_n = \sum_{m=1}^{q} \left[\left(\frac{env_{m,n}}{\left(\frac{\sum_{n=1}^{p} env_{m,n}}{p} \right)} \right) w_m \right] \tag{3.11}$$

where $eco_{m,n}$ is the impact of economic indicator m for case study n, $soc_{m,n}$ is the impact of social indicator m for case study n, $env_{m,n}$ is the impact of environmental indicator m for case study n, w_m is the weighting applied for each indicator depending on the categories importance, q is the number of indicators evaluated in each of the economic, social and environmental categories and p is the number of case studies evaluated. The sum of the weightings ($\Sigma(w_m)$) applied to indicators in each category must add up to one. As can be seen from Equation 3.8, each of the three categories for the SIF can be given a different weighting depending on the importance each of the three categories. Furthermore, the indicators in each of the categories can be given a different weighting depending on their importance.

This SIF methodology can be used for assessing the SIF impact of a set of buildings which are representative of a country's national building stock for a number of economic, social and environmental indicators.

3.2.7 Sensitivity Analysis

The life cycle cost and life cycle environmental results are influenced by the assumptions made with regards to the discount rate, energy prices and efficiency of the electricity grid. A baseline 4% discount rate is assumed in addition to the static energy prices and electricity grid efficiency for the lifespan of the building. Therefore, a sensitivity analysis is carried out to see what influence the assumptions made in terms of the discount rate, energy prices and efficiency of the electricity grid have on the results.

3.2.7.1 Discount rate

The discount rate effects the OEC of the case study buildings. Therefore, an analysis is done to determine the impact a varying discount rate has on the annual OEC using the present value of an annuity (PVA) formula. The PVA for case study n can be expressed mathematically as:

$$PVA_n = \frac{OEC_x}{r}\left(1 - \frac{1}{(1+r)^y}\right) \tag{3.12}$$

where OECx is the annual operational economic cost (€/year), r is the discount rate (%) and y is the number of years in the building's life cycle.

The impact of a varying discount rate on the equivalent annual cost (EAC) of constructing and operating the building over its lifespan is also assessed. The EAC of case study n can be expressed mathematically as:

$$EAC_n = {}^{(NCC).r}\Big/_{\left(1 - \frac{1}{(1+r)^y}\right)} + \text{OECx} \tag{3.13}$$

where NCC is the net construction cost (€), OECx is the annual operational economic cost (€/year), r is the discount rate (%) and y is the number of years.

3.2.7.2 Energy Costs

For the baseline analysis, the energy prices are assumed to remain constant for the lifespan of the buildings. In reality, throughout a building's 60-year lifespan, energy prices are not going to remain constant and may have a significant impact on the hierarchy of the case studies life cycle costs. Therefore, a sensitivity analysis is carried out using projected future energy costs. Future energy prices are predicted, based on the average annual growth rate of historical energy prices which are discussed in later sections.

3.2.7.3 Electricity Generation Fuel Mix

For the baseline analysis, the electricity generation fuel mix, which effects the efficiency of the electricity grid and its GWP intensity, is assumed to remain constant for the building's life cycle. Decarbonising electricity generation in Ireland is seen as one of the key measures to transitioning to a low carbon, climate resilient and environmentally sustainable economy by 2050 [77]. A sensitivity analysis is carried out to determine what impact the Irish electricity grid becoming more decarbonised and efficient has on the results.

SEAI have projected Ireland's energy demand across multiple sectors including electricity generation until 2035 [254]. Using the data [255], the conversion efficiency and primary energy factor for each of the energy sources used in electricity generation are calculated.

Ecoinvent (v3.4) [256] provides the energy, GWP, ODP, AP, EP, and POCP intensities per MJ_{del} of electricity generated in Ireland during 2017. Ecoinvent (v3.4) [256] also provides the energy, GWP, ODP, AP, EP and POCP intensities per MJ_{del} of electricity generated for fossil fuel and renewable energy sources used in the generation of electricity in Ireland. The data from Ecoinvent (v3.4) on the environmental impact of fossil fuel and renewable energy sources electricity generation is based on power plants in Ireland in 2012 which has been extrapolated to 2017. An example of the GWP per MJ of different energy sources used for electricity generation in Ireland during 2014 is given in Table 3.1.

To estimate the annual GWP intensity of the electricity grid up 2035, the annual secondary energy contribution of fossil fuels and renewable energy sources for electricity generation sourced from SEAI are multiplied by the energy source intensities of Ecoinvent (v3.4) [256] to calculate the total primary GWP for electricity generation. As shown in Table 3.2 for the calculated primary energy factor of peat, the conversion efficiency is found to change over time. Any change in conversion efficiency for the energy sources is assumed to occur for the GWP MJ_{del} values given in Table 3.1.

Table 3.1: GWP per MJ of fossil fuels and renewable energy sources used in electricity generation in Ireland (Source: Ecoinvent (v3.4) [256]*).*

Energy Source	GWP/MJ_{del}
Coal	0.301
Oil	0.255
Gas	0.105
Peat	0.285
Wind <1MW	0.003
Wind >3MW	0.006
Wind 1-3MW	0.004
Hydro-Pumped Storage	0.234
Hydro-Run of River	0.001

Using the calculated total primary GWP from electricity generation divided by the total secondary energy for electricity generation, annual GWP/MJ_{del} of electricity generated intensities for the Irish electricity grid up to 2035 are estimated. This process is repeated for the energy, OCP, AP, EP and POCP indicators to estimate the change in the impact of each indicator as the grid becomes decarbonised. The calculated average annual growth rates of the indicators per MJ_{del} in electricity generation from 2014-2035 and from 2028-2035 are shown in Table 3.3.

Table 3.2: Calculated primary energy factor of peat for electricity generation in Ireland.

Energy Source	MJ_{prim}/MJ_{del}											
	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Peat	2.70	2.63	2.63	2.66	2.66	2.66	2.63	2.63	2.63	2.63	2.63	2.63

As can be seen in Table 3.3, the Irish electricity grids environmental impact is expected to reduce across all environmental indicators between 2017 and 2035. Demand for electricity in Ireland is expected to grow up to 2035. Even though renewable energy is expected to contribute to the growth in electricity demand, gas is expected to be the main energy source for electricity generation in Ireland by 2035. Peat's contribution to electricity generation is expected to drastically reduce from 2020 and is predicted to be phased out of electricity generation by 2026. Coal's contribution to electricity generation has grown the last number of years, but is expected to start reducing from 2024 onwards before having a marginal contribution from 2028 onwards.

Table 3.3: Average annual growth rates of the indicators impact per MJ of electricity generated from 2014-2035 and 2028-2035.

	Average Annual Growth Rate (%)	
Environmental Indicator	2017-2035	2028-2035
EN	-1.07	-0.11
GWP	-1.21	-0.10
ODP	-0.07	-0.07
AP	-1.26	0.07
EP	-0.94	0.02
POCP	-0.63	0.02

GWP, ODP, AP, EP, POCP are all related to the emission of substances to the earth's atmosphere. This analysis does not account for any additional processes that may be installed to mitigate the emission of substances to the earth's atmosphere in the future.

Beyond 2035, the average annual growth rates of the indicators' impact per MJ of electricity generated from 2028-2035 are used to estimate the change in the impact of the indicator (Table 3.3). Peat and coal are predicted to have been phased out or their contribution marginalised in electricity generation by 2028. AP, EP and POCP are expected to grow marginally between 2028-2035 as the contribution of oil to the electricity generation fuel mix is projected to increase marginally in this period. The projections on the changes in the electricity grid decarbonisation and primary energy factor are used in the analysis of Chapter 3. The six environmental indicators for electricity generation are used in the analysis of Chapter 4.

In the case studies which export electricity to the grid, the GWP savings are assumed to have the same GWP intensity of the electricity grid for that given year. Other studies have suggested using the same GWP intensity as the electricity grid initially, before plateauing due to the GWP intensity of the marginal power plant supplier. Eventually the GWP intensity of the electricity supply would start declining again due to the increasing decarbonisation of the electricity fuel supply [257]. This would have minimal impact on the total GWP results of the case studies as the GWP intensity would reach the same intensity at some point in the future in these scenarios. Therefore, the exported electricity is assumed to have the same GWP intensity as the electricity grid. The same assumption is made with regards to the electricity primary energy factor.

The GWP and primary energy savings made through the installation of renewable technology vary throughout the year. The savings made by the renewable technology depend mainly on the varying energy demands of the case study buildings throughout the year, the varying energy production levels caused mainly by the levels of global radiation in Ireland throughout the year, and the GWP and primary energy factor for the main grid electricity generation during the year.

Total CO_2 emissions and energy demand of the electricity grid are sourced from Eirgrid [258], the company that manages and operates the transmission grid across the island of Ireland). The GWP impact of the Irish electricity grid for the months during 2014 and 2015, together with their average monthly emissions intensities for 2014 and 2015, are given in Figure 3.2. As can be seen from Figure 3.2, the GWP intensity of the electricity grid in Ireland is similar throughout the year with a maximum 20% difference in average monthly values and a standard deviation of 0.008 $kgCO_{2eq}/MJ$ in the average monthly values.

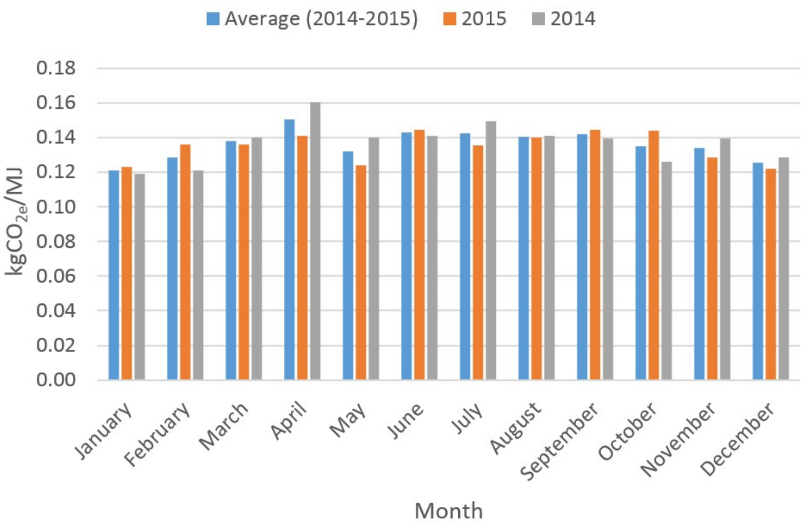


Figure 3.2: GWP impact of the Irish electricity grid for the months 2014 and 2015.

The average global radiation (sourced from Met Éireann [259], the Irish National Meteorological Service) of five weather stations in Ireland (Mace Head, Malin Head, Cork Airport, Dublin Airport and Mullingar) for 2014 and 2015, together with monthly averages for the period 2013 to 2015, are given in Figure 3.3. The large variability in the global radiation for the different months of the year does not significantly affect the GWP intensity of the electricity grid in Ireland, as PV is a very small contributor of electricity supplied to the grid (i.e. < 0.001% as of 2013) [260]. Comparing the use of average yearly and monthly factors in determining both the GWP and operational energy of the case study buildings, it is found that the largest percentage difference to be less than 5%. As this is minimal, an average yearly GWP and primary energy factor for the electricity grid is assumed for the results of this chapter.

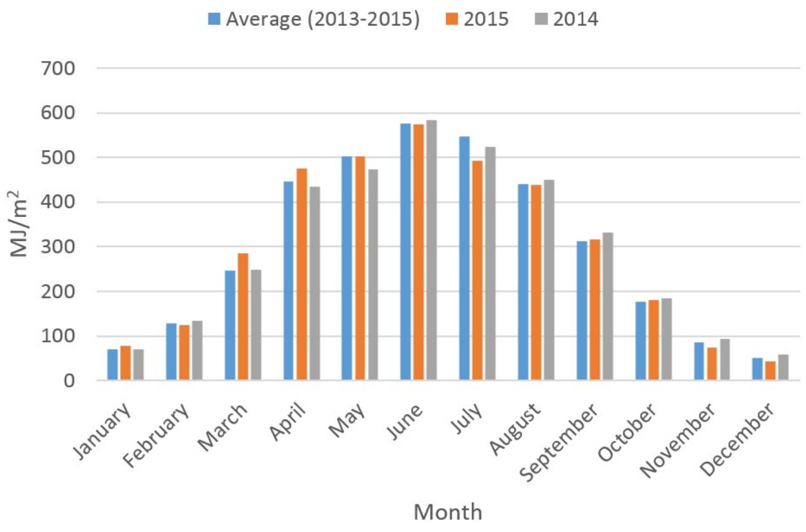


Figure 3.3: The average global radiation of five weather stations in Ireland (Mace Head, Malin Head, Cork Airport, Dublin Airport and Mullingar) for 2014 and 2015 along with their average for 2013-2015.

3.3 Theoretical Case Study Building

Case study buildings for LCA are typically chosen due to the prevalence of a building type in the reference country [261]. In Ireland, semi-detached houses are Ireland's second most common dwelling type accounting for 471,928 of the occupied dwellings and the second most common house type constructed in the 2000's [262]. Irish households rely on predominantly oil (37.9%) and gas (35.2%) as the main fuel heat source. Semi-detached houses are the most common gas heated housing type (41%) in Ireland and terraced houses are the second most common gas heated housing type (29%) [262].

A theoretical south orientated semi-detached residential two storey masonry building (106 m^2 heated floor area) is chosen as a case study design template (Figure 3.4). The 3-bedroom house is a gas-to-water space heated dwelling, with features typical of residential construction practices in many Irish homes [263].

3.4 Results

3.4.1 Environmental and Economic Impact of Changing Energy Performance Building Regulations

Six different versions of the theoretical semi-detached building were investigated to assess how the embodied share of a building's life cycle is changing due to revisions in the building regulations to achieve nZEB standard. In addition, environmental hot spots from past practices in building construction that need to be mitigated to reduce the environmental impact of future Irish building construction practices were assessed. Energy (MJ) and GWP ($kgCO_{2eq}$) were used as the environmental indicators in this analysis.

Table 3.4 shows the maximum U-values (W/m^2K) specified in Irish building regulations for building elements since 2005. Passive house standards do not specify maximum building element U-values [264]. Passive houses though are required to have an annual heating energy demand of 15 $kWh/m^2/yr$ [264]. Building element U-values for a semi-detached Irish house [264] are included in Table 3.4. Table 3.5 summarises the differences in the case study buildings in terms of their building standard, ventilation method, air-tightness and ventilation method characteristics. Table 3.6 summarises the differences in the case study buildings in terms of their space and water heating systems and installed renewable technologies. Energy and GWP intensity values for the space and water heating energy sources and renewable technology are sourced from Refs. [265]–[268]. Table 3.7 summarises building elements of the case study houses.

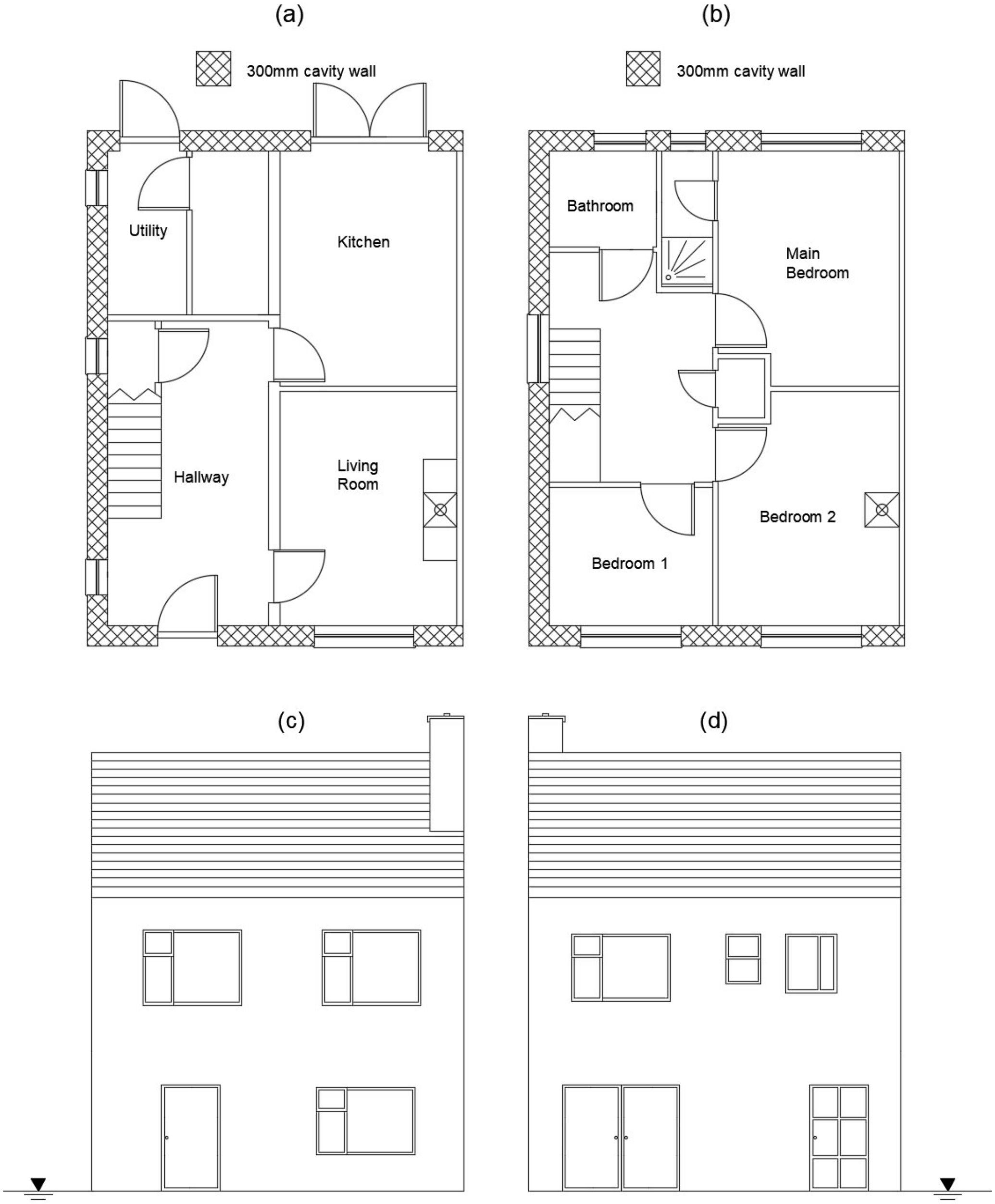


Figure 3.4:(a) Ground floor layout, (b) First floor layout, (c) Front façade and (d) Back façade of theoretical case study semi-detached house.

The first two case study buildings complied with 2005 and 2007 Irish residential building energy performance regulations Technical Guidance Document (TGD) Part L, respectively [23], [97]. Natural ventilation (i.e. trickle and purge ventilation) was used in the living room and bedrooms. Kitchen, bathrooms and utility room were mainly ventilated with the help of mechanical extract fans with an extract rate of $10m^3/h$ each. However, the practice of ventilating the house through opening windows is generally not welcomed by Irish householders in all seasons, due to Ireland's temperate oceanic climate with cold and humid winters. People can be reluctant to open windows to allow the cold fresh air inside. Trickle vents in windows and walls are often closed or blocked-off by building occupants. Particularly if vents are facing towards the prevailing wind in an exposed site or on northerly façade of the building, from which the colder winds come.

DEAP assumes the heating system operates from 7:00 to 9:00 and 17:00 to 23:00 seven days a week. The set point temperature of the living area during the heating periods is 21°C and 18°C in the rest of the dwelling. During heating hours, the required mean internal temperature of the dwelling is calculated as the average of the set-point temperatures in the living area and in the rest of the dwelling, weighted by floor area.

Table 3.4: Maximum U-values (W/m^{2}K) specified in Irish Building Regulations [23], [24], [28], [97] *and passive house U-values for a semi-detached house* [264].

Building Elements			U Value (W/m^{2}K)				
			Building Regulations				
			2005	2007	2011	2019*	Passive House
Roofs	Pitched Roof	Insulation on Ceiling	0.16	0.16	0.16	0.16	0.15
		Insulation on Slope	0.2	0.16	0.16	0.16	
	Flat Roof		0.22	0.22	0.2	0.2	
Walls			0.27	0.27	0.21	0.18	0.175
Ground Floors			0.25	0.25	0.21	0.18	0.15
External Doors, Windows and Rooflights			2.2	2	1.6	1.4	0.8

Note: *2019 building element U-values based on draft 2019 building regulations which are expected to be published in Q3 2019 and enforced from September 2019 [28].

The next two case studies (case study 3a and 3b) complied with the 2011 Irish residential building energy performance regulations TGD Part L [24] using two different design strategies. The first strategy (case study 3a) achieved compliance using building fabric, ventilation and air-tightness performance characteristics which pass 2011 Irish Building Regulations requirements [24], [269]. The second design strategy (case study 3b) focused on a building with a higher building fabric thermal efficiency performance. It achieved compliance with the 2011 Irish residential building energy performance regulations using building fabric, ventilation and air-tightness performance characteristics which meet passive house standards [264] with less reliance on renewable energy technologies (see Table 3.5, Table 3.6 and Table 3.7)

Table 3.5: General characteristics of the six case studies.

Case Study	Building Energy Standard	Air-tightness	Ventilation	Mechanical Ventilation System Characteristics
No.		(ac/hr @ 50 Pa)		SPF: W/l/s; HRE: %
1	2005	9.1	NV and MV	N/A
2	2008	5.44	NV and MV	N/A
3a	2011	5.44	NV and MV	N/A
3b	2011	0.45	MVHR	SPF: 1.04; HRE: 89
4a	nZEB	5.44	NV and MV	N/A
4b	nZEB	0.45	MVHR	SPF: 1.04; HRE: 89

Abbreviations

HRE: Heat Recovery Efficiency
MV: Mechanical Ventilation (Extract Fan of 10m^3/h in kitchen and bathrooms)
MVHR: Mechanical Ventilation with Heat Recovery
NV: Natural Ventilation (Purge Ventilation via windows in habitable room and open flue in living room)
SPF: Specific Fan Power

Table 3.6: Space and water heating systems and installed renewable technologies of the case study buildings.

Case Study	Main and *Secondary Heating System	Efficiency Heating System	Renewable Technology	
No.			ETSC (m^2)	MCPV (m^2)
1	Gas Boiler and Gas Fire	Main: 80.5%, Sec: 80%	0	0
2	Gas Boiler and Gas Fire	Main: 91.3%, Sec: 80%	3.23	0
3a	Gas Boiler and Gas Fire	Main: 91.3%, Sec: 80%	6.46	9
3b	Gas Boiler and Gas Fire	Main: 91.3%, Sec: 80%	3.23	0
4a	Gas Boiler and Gas Fire	Main: 91.3%, Sec: 80%	6.46	16
4b	Gas Boiler and Gas Fire	Main: 91.3%, Sec: 80%	6.46	3

Abbreviations

ETSC: Evacuated Tube Solar Collector
MCPV: Multi-crystalline Photovoltaic
SPF: Seasonal Performance Factor
*Secondary heating systems account for 10% of space heating requirements

The final two case studies (case study 4a and 4b) complied with the forecast new build nZEB Irish residential building energy performance target (Table 1.1) using two different strategies. The first strategy (case study 4a) focused on the use of renewable technologies to achieve the nZEB energy performance standard. It achieved compliance using the same building fabric, ventilation and air-tightness strategy as case study 3a (Table 3.5 and Table 3.7). The amount of renewable technologies installed in the building increased to achieve the nZEB energy performance standard

(Table 3.6). The second strategy (case study 4b) focused on a building with a high building fabric thermal efficiency performance. The same design strategy as case study 3b was utilised (Table 3.5 and Table 3.7) but included additional renewable technologies to achieve the nZEB energy performance standard (Table 3.6).

An evacuated tube solar collector (ETSC), with an aperture area of 3.23 m^2 area and 0.727 zero loss collector efficiency and multi-crystalline photovoltaics (MCPVs) with a 13.2% efficiency were the utilised renewable technologies. For a south orientated building in Ireland, annual solar radiation of 3866 MJ/m^2 was assumed [25]. The mechanical ventilation heat recovery (MVHR) unit was assumed to have a specific fan power of 1.04 W/l/s and heat recovery efficiency of 89% for case studies 3b and 4b. As it is a common practice in Ireland, a secondary space heating system, i.e. a gas fire, was included in the living room of each of the case study buildings. The EE and EC of the gas fire was not accounted for in the analysis. A schematic of the heating and electricity system of the case study buildings is shown in Figure 3.5. An ETSC system was used in tandem with the gas boiler for the generation of hot water for domestic purposes.

MCPV panels were used to generate electricity for the pumps, ventilation and lighting requirements of the case study buildings. It did not account for the use of domestic appliances due to the limitations of DEAP [25]. The MCPV system allowed generated electricity not consumed by the case study buildings to be exported back to the electricity grid. The price of MCPV had drastically decreased [270] since the publication of Spon’s Construction Price Book (2008) [247]. Therefore, 2013 price of photovoltaic systems in Italy was assumed as the price of MCPV in this analysis [270].

The primary energy conversion factor of electricity and gas were taken as 2.37 MJ_{prim}/MJ_{del} and 1.10 MJ_{prim}/MJ_{del} [25], respectively, throughout the building’s 60-year life cycle. The GWP intensity conversion factor of electricity and gas were taken as 0.145 $kgCO_2/MJ$ and 0.056 $kgCO_2/MJ$ [25], respectively, throughout the building’s 60-year life cycle. Using the delivered energy of the respective fuels to each of the case study buildings and Irish residential energy prices [271], [272], operational costs of the case study buildings were determined. 2014 Irish residential electricity and gas prices of 0.055 €/MJ and 0.016 €/MJ, respectively, were assumed for the results of this analysis [271], [272] and did not include VAT. Residences in Ireland were offered

2.5 c/MJ to export electricity onto the national grid up to 2016 [273]. Standing charges for energy companies were excluded from the analysis.

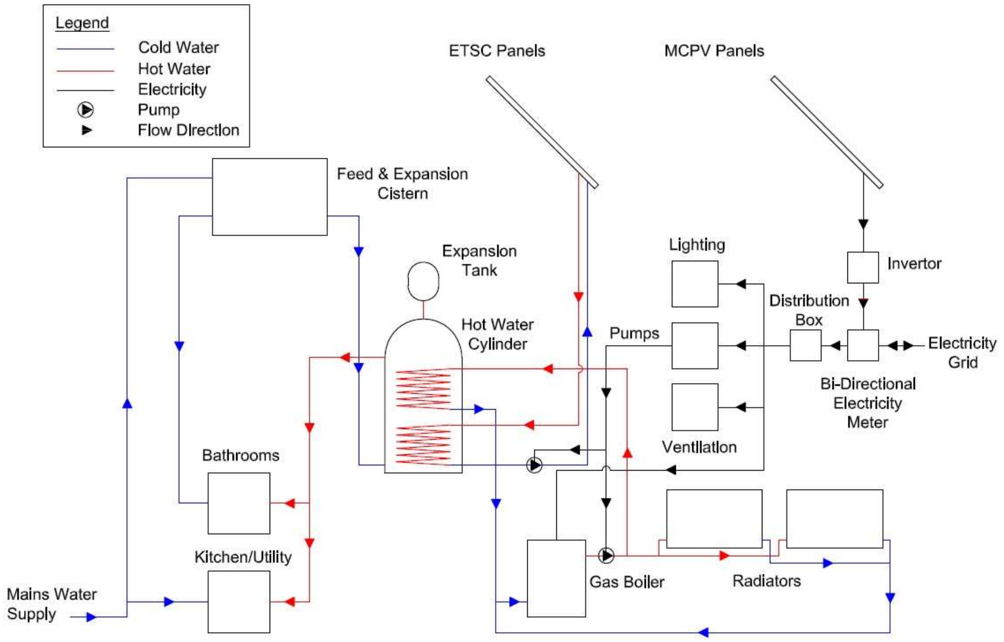


Figure 3.5: Schematic of the case study buildings heating and electrical system.

Table 3.7 summarises the EE, EC and U-values of the building element systems utilised in the six case study buildings. The functional unit of each of the systems is the surface area (m^2). U-values for typical external wall, pitched roof and floor systems are determined according to Ref. [24]. Figure 3.6(a)-(c) demonstrates the calculated energy, GWP and economic breakdown of each of the analysed case studies. windows, introduction of a more efficient gas boiler, improved air-tightness and the installation of an ETSC. An increase of 2.3% in EE lead to a reduction of 30.2% in the baseline OE. The investment in EE and EC were both paid back in less than a year due to the operational savings.

Table 3.8 highlights the percentage increase in terms of energy, GWP and economic costs of each of the case study buildings compared to the case study designed to meet the minimum standards set out in the 2005 Irish Building Regulations [23].

A1-A3/'cradle-to-gate' process based EE and EC intensities per m^2 of heated floor area were 3619 MJ/m^2 and 369 kgCO$_{2eq}$/m^2, respectively, for the baseline scenario (case study 1) (Figure 3.6(a)-(b), windows, introduction of a more efficient gas boiler, improved air-tightness and the installation of an ETSC. An increase of 2.3% in EE lead to a reduction of 30.2% in the baseline OE. The investment in EE and EC were both paid back in less than a year due to the operational savings.

Table 3.8). A life cycle energy breakdown of 89% and 11% for OE and EE, respectively, was found for case study 1 (Figure 3.6(a)). OC and EC were responsible for 81% and 19%, respectively, of life cycle GWP accounted

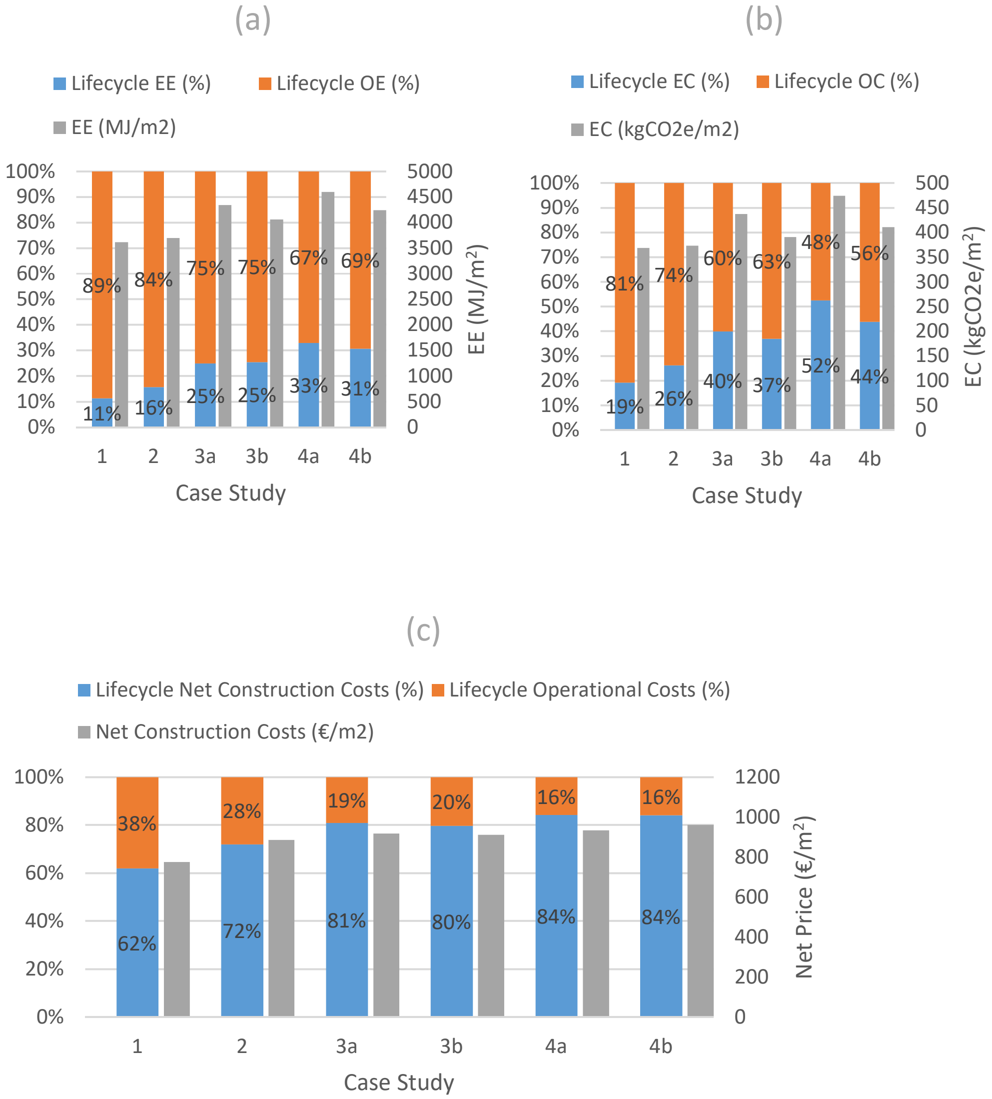


Figure 3.6: (a) Estimated life cycle energy including embodied energy (EE), (b) Estimated life cycle GWP breakdown including embodied global warming potential (EC), (c) Estimated life cycle economic breakdown including net construction costs (NCC) of a typical semi-detached home in Ireland over a 60-year lifespan.

for in this analysis (Figure 3.6(b)). From the economic analysis, an NCC of €776/m^2 was estimated. This was the lowest recorded net construction cost calculated for all case study houses (Figure 3.6(c)). The OEC over a 60-year period was €477/m^2 for case study 1, assuming no change in fuel prices and no further retrofitting.

The lowest investment in EE and EC which produces the largest OE and EC savings was moving from the 2005 [23] to the 2008 Building Regulations [97] (windows, introduction of a more efficient gas boiler, improved air-tightness and the installation of an ETSC. An increase of 2.3% in EE lead to a reduction of 30.2% in the baseline OE. The investment in EE and EC were both paid back in less than a year due to the operational savings.

Table 3.8). The main differences between both scenarios were the improvement in the U-value of

Table 3.7: Descriptions, U-values (W/m^{2}K), EE (MJ/m^2) and EC (kgCO$_{2eq}$/m^2) of the building element systems utilised in the case study buildings per m^2 of surface area.

Descriptions	Case Study	U-Value	EE	EC
Typical external wall systems*				
Cavity block wall, 440x225x100mm dense concrete masonry block internal and external leaf, 80mm cavity rigid board insulation (λ=0.023W/mK), 40mm residual cavity air gap, 19mm external render, 12.5mm internal plaster, 5mm gypsum plaster coat ('skim coat'), 3 layers waterborne paint each side	1, 2	0.27	329	30
Cavity block wall, 440x225x100mm dense concrete masonry block internal and external leaf, 100mm cavity rigid board insulation (λ=0.023W/mK), 40mm residual cavity air gap, 29.5mm internal drylining insulation board (λ=0.023W/mK), 19mm external render, 5mm gypsum plaster coat ('skim coat'), 3 layers waterborne paint each side	3a, 4a	0.20	432	36
Cavity block wall, 440x225x100mm dense concrete masonry block internal and external leaf, 120mm cavity rigid board insulation (λ=0.023W/mK), 40mm residual cavity air gap, 29.5mm internal drying insulation board (λ=0.023W/mK), 19mm external render, 5mm gypsum plaster coat ('skim coat'), 3 layers waterborne paint each side	3b, 4b	0.17	459	37
Typical internal wall systems				
Solid block wall, 440x225x100mm dense concrete masonry block, 12.5mm sand and cement plaster each side, 5mm Gypsum plaster coat ('skim coat'), 2 layers waterborne paint each side	1, 2, 3a, 3b, 4a, 4b	-	252	29
Timber frame wall, 12.5mm sheathing board covering timber studs, 5mm Gypsum plaster coat ('skim coat') each side, 2 layers waterborne paint each side	1, 2, 3a, 3b, 4a, 4b	-	375	12

Typical pitched roof systems				
Standard timber gable-end roof, rafters (44x175mm), ceiling joists (44x225mm), ceiling insulation 275mm fibreglass (λ=0.044W/mK), synthetic slates finish	1, 2	0.15	671	42
Standard timber gable-end roof, rafters (44x175mm), ceiling joists (44x225mm), ceiling insulation 300mm fibreglass (λ=0.044W/mK), synthetic slates finish	3a, 4a	0.14	683	43
Standard timber gable-end roof, rafters (44x175mm), ceiling joists (44x225mm), ceiling insulation 350mm fibreglass (λ=0.044W/mK), synthetic slates finish	3b, 4b	0.12	707	44
Typical window openings system				
12mm double glazed argon filled PVC framed windows, low E, en=0.2	1	2.1	560	182
12mm triple glazed argon filled PVC framed windows, low E, en=0.05	2, 3a, 4a	1.4	592	181
20mm triple glazed argon filled PVC framed windows, low E, en=0.05	3b, 4b	0.8	600	181

Table 3.7: Descriptions, U-values (W/m^{2}K), EE (MJ/m^2) and EC (kgCO$_{2eq}$/m^2) of the building element systems utilised in the case study buildings per m2 of surface area (continued).

Descriptions	Case Study	U-Value	EE	EC
Typical floor and foundation systems				
C20 strength concrete strip foundation with 4% steel reinforcement (width 900mmx depth 300mm), 100mm rigid board insulation (λ=0.035W/mK), damp proof membrane and radon barrier included, 75mm concrete screed with vinyl floor finish	1, 2	0.23	1,999	199
C20 strength concrete strip foundation with 4% steel reinforcement (width 900mmx depth 300mm), 120mm rigid board insulation (λ=0.031W/mK), damp proof membrane and radon barrier included, 75mm concrete screed with vinyl floor finish	3a, 4a	0.18	2,063	201
C20 strength concrete strip foundation with 4% steel reinforcement (width 900mmx depth 300mm), 150mm rigid board insulation (λ=0.031W/mK), damp proof membrane and radon barrier included, 75mm concrete screed with vinyl floor finish	3b, 4b	0.15	2,158	205
200mm hollow core concrete suspended floor with 10mm wood timber flooring and adequate gypsum ceiling plasterboard finish	1, 2, 3a, 3b, 4a, 4b	-	703	72

Note: *U-values include a correction factor of 0.02 W/m^{2}K accounting for the use of wall ties

windows, introduction of a more efficient gas boiler, improved air-tightness and the installation of an ETSC. An increase of 2.3% in EE lead to a reduction of 30.2% in the baseline OE. The investment in EE and EC were both paid back in less than a year due to the operational savings.

Table 3.8: Percentage change in terms of energy, GWP and costs of case studies compared to baseline case study (case study 1).

		Difference (%)				
Indicators	Baseline-Case 1	2	3a	3b	4a	4b
EE	382,983 MJ	2	20	12	27	17
OE	3,005,365 MJ	-30	-54	-58	-67	-66
EC	39,004 $kgCO_{2e}$	1	19	6	29	11
OC	164,031 $kgCO_{2e}$	-32	-58	-57	-72	-66
Construction Cost	€82,138	14	18	18	20	24
Operational Cost	€50,475	-28	-55	-51	-63	-62

3.4.1.1 Insulation or Renewable Technology for nZEB Building

Two different design scenarios were investigated in order to achieve the 2011 building energy performance standards [24] (case study 3a and 3b) and nZEB energy performance standards (case study 4a and 4b). Scenario 3a and 4a focused more on the installation of renewable technologies (ETSC and MCPV), with building fabric thermal efficiency, air-tightness and ventilation strategies only achieving the minimum requirements set out in the current Irish Building Regulations [24], [269]. Scenario 3b and 4b focused on utilising a high thermal efficiency building fabric performance with a smaller amount of renewable technology to achieve 2011 building energy performance standards [24] and nZEB building energy performance targets.

The design method had a significant impact on achieving a building that complies with 2011 regulations. The strategy that focused on a high thermal fabric efficiency performance outperforms its renewables strategy counterpart in terms of both EE and EC. This was due to the high embodied impact of MCPV. The strategy that focuses on a high thermal fabric efficiency performance outperformed the renewables strategy counterpart in terms of OE, but not in terms of OC. Case study 4a and 3a produced the first and third smallest GWP impact during their operational phase, respectively. This was due to the high primary GWP factor of the Irish electrical grid (0.145 $kgCO_2/MJ$) and the savings caused by the large installation of MCPV in both case studies. However, with the electricity grid expected to become more decarbonised, the impact of the MCPV in reducing a building's operational GWP impact will be less significant in the future [107]. Case study 4b consumed the least amount of energy during its lifespan compared to others. In fact, the design case study 4b required 104 MJ/m^2 of EE less than case study 3a and 362 MJ/m^2 less than the case study 4a.

Despite the operational cost of the renewables focused strategy being less than the building fabric focused strategy, over the life span of the building it was better to focus on the building fabric rather than renewables. To achieve an nZEB energy performance standard for case studies 4a and 4b, more renewable technology was installed in comparison to case studies 3a and 3b. In fact, due to the large amount of MCPV installed in case study 4a and 3a, the buildings were exporters of electricity onto the electrical grid. In this analysis, the exported electricity was considered avoiding electricity generation. Thus, the GWP and primary energy usage were reduced accordingly and included as part of the use stage of the case study buildings' life cycle assessment (Module B6). Case study 4a and 3a annually earned €93 and €22 for exporting electricity, respectively. With this annual earning for exporting electricity, case study 4a had the lowest annual OEC. If there was no price given for electricity to be exported back onto the national grid, case study 4a would no longer have been the design with the optimal OEC. Case study 4b would have been the optimum solution in terms of OEC.

3.4.1.2 Mechanical Ventilation with Heat Recovery (MVHR) System

One of the main differences in moving from 2011 building air-tightness standards to passive air-tightness standards in this analysis was the introduction of a MVHR system. The EE and EC results of the MHRV unit and associated ducting are provided in Table 3.9. The list of materials is based on a ProAir PA 600LI heat recovery ventilation system [274]. The embodied impacts of the materials were sourced from the ICE database [109]. If the material intensity did not exist within this database, the Cumulative Energy Demand (MJ/kg) and Global Warming Potential (kgCO$_{2e}$/kg) material impacts were sourced from the Ecoinvent V.2 database [275]. The component with the largest EE impact was the ducting used for the supply and extraction of air from the building. This highlighted the impact of developing an efficient design with the minimum amount of ducting for a ventilation system within a building.

Table 3.9: EE and EC impact associated with MHRV system.

Component	EE		EC	
	MJ	%	kgCO$_{2e}$	%

Main Insulation Foam	407	6.6	266	40.2
Unit Steel Frame	224	3.6	16	2.5
Heat Exchanger	484	7.9	19	2.9
Fans	203	3.3	12	1.8
Fans Casing	244	4.0	119	18.0
Supply and Extract Ducting	4146	67.4	198	30.0
Supply and Extract Terminals	27	0.4	1	0.2
Supply and Extract Distribution Boxes	78	1.3	13	1.9
Air Filters	8	0.1	1	0.1
Thermal and Acoustic Insulation Ducts	80	1.3	4	0.7
Circular Connections for Supply and Extract Points of MHRV Unit	15	0.2	1	0.2
Sealants	233	3.8	10	1.5
Total	6148	100	661	100

The impact of removing the extract fans installed in case study 4a and increased air-tightness reduced the OE of the building by 28.1 MJ/m^2/year. The introduction of the MHRV unit and associated ducting reduced the OE by a further 40.8 MJ/m^2/year. It, therefore, would take 1.4 years for the MVHR unit to recover the energy used in the manufacturing of the system and 3.5 years to recover the GWP emitted in the manufacturing phase.

For case study 4b, the interaction of the building's envelope materials had a large impact on the operational savings of the MVHR. If the extract fans installed in case study 4a were removed, the air-tightness increased, the U-values of the thermal envelope improved to passive standards and the MVHR system installed, an OE saving of 28.7 MJ/m^2/year was achieved by the MVHR system. This resulted in an energy payback period of 2 years for the MVHR unit to recover the energy used in the manufacturing of the system and 4.3 years to recover the GWP gases emitted in the manufacturing phase. In terms of the overall EE and EC of case study 4b, the MVHR system accounted for 1.4% and 1.5%, respectively.

3.4.1.3 Material 'Hot Spots'

The material 'hot spots' of each of the studied building assemblies in terms of EE and EC are shown in Figure 3.7. The superstructure (walls, foundations and floors) were the biggest EE and EC contributors in each of the case studies similar to findings from other studies (see, for example, [35], [86], [89], [90], [92]).

The EE contribution to life cycle energy of the case study buildings increased with each iteration of the building regulations. For case study 1, the EE and EC contributed 11% and 19% of the building's environmental life cycle impact. For the two nZEB case studies (4a and 4b), the EE contribution increased to 33% and 31%, while the EC contribution increased to 52% and 44%, respectively. Thus, with OE and OC beginning to have less of an impact on the life cycle of a building, architects and engineers will need to start focusing more on reducing the impact of these hot spots in a building's life cycle.

For example, in the case study building, the first floor was designed using a concrete hollow core slab. If a suspended timber floor was specified instead, the EE and EC impact of the floor reduced to 2195 MJ and 59 $kgCO_{2e}$ compared to the 25709 MJ and 3331 $kgCO_{2e}$ associated with a hollow core concrete floor. This reduced the EE impact of the life cycle energy of the nZEB case studies to 32% and 30% and the EC impact of the life cycle GWP to 51% and 42%, respectively.

Similar for the roofing system. The specified fibre slate tile had an impact of 10113 MJ and 1245 $kgCO_{2e}$. If a concrete tile was specified instead of the fibre slate, the EE and EC increased to 29120 MJ and 213 $kgCO_{2e}$ respectively. This increased the EE impact of the nZEB case studies to 34% and 32% and increased the EC impact to 52% and 43%, respectively.

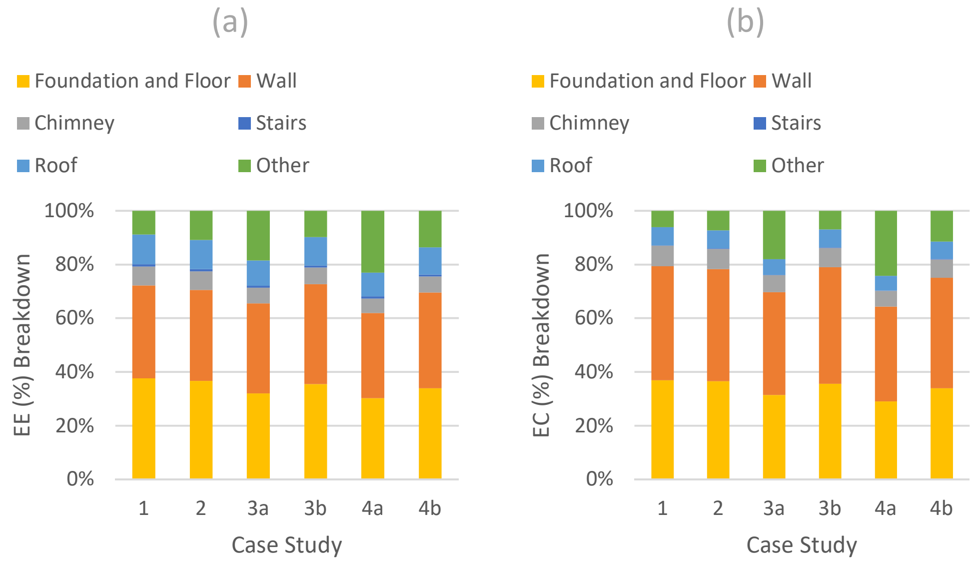


Figure 3.7: (a) EE and (b) EC breakdown of case study houses according to segregated building assemblies.

3.4.2 Design Strategy for an Irish nZEB Building: Super-Insulate or Renewable Technology

From reviewing the studies in Table 2.1, Table 2.2 and Table 2.3 and the results of Section 3.4.1, the environmental and economic life cycle results were impacted by different thermal fabric efficiencies and different heating system design strategies. The environmental and economic impact for various thermal fabric efficiency and heating system design strategies for new build nZEB semi-detached residential buildings in Ireland were examined in the following section.

Eight different versions of the theoretical semi-detached house presented in Section 3.3 were investigated with two different building fabrics, air-tightness and ventilation strategies employed. Case studies one to four achieved the expected nZEB minimum energy performance target [276], while also adhering to 2011 Irish residential building regulation requirements for building fabric, air-tightness and ventilation [24], [269].

Case studies five to eight complied with passive house building fabric, air-tightness and ventilation standards to achieve the minimum nZEB energy performance target [277]. Table 3.10 summarises the differences in the case study buildings in terms of building envelope thermal efficiencies, air-tightness characteristics and ventilation method.

Table 3.10: Characteristics of the building envelope and ventilation systems for the eight case studies.

Case Study	External Wall	Roof	Floor	Window	Air-tightness	Ventilation	Mechanical Ventilation System Characteristics	
No.	U-Value (W/m^2/K)				(ac/hr @ 50 Pa)		SPF (W/l/s)	HRE (%)
1-4	0.20	0.14	0.18	1.40	5.44	NV and MV	N/A	N/A
5-8	0.17	0.12	0.15	0.80	0.45	MVHR	0.89	90

Abbreviations

HRE: Heat Recovery Efficiency
NV: Natural Ventilation (Purge Ventilation via windows in habitable rooms and open flue (20 m^3/h) in living room)
MV: Mechanical Ventilation (Extract Fan of 10 m^3/h in kitchen, utility room and bathrooms)
MVHR: Mechanical Ventilation with Heat Recovery
SPF: Specific Fan Power

The eight case studies utilised different strategies for providing space and water heating needs, including a condensing gas boiler, a biomass boiler for wood pellets, a domestic gas-fired combined heat and power (CHP) unit, a heat pump system covering 75% of the total water heating demand (the remaining is covered by electricity) and varying amounts of renewable technology. A wood stove was specified to act a secondary space heating system in the living room of each of the case study buildings. The open flue for the wood stove was assumed to have a ventilation rate of 20 m^3/h. Each of the heating sources worked in tandem with varying amounts of renewable energy technology. The renewable energy technologies employed included ETSCs and MCPVs. One ETSC had an aperture area of 3.23 m^2 and 0.727 zero loss collector efficiency. The MCPV had an efficiency of 13.2%. For a south orientated building in Ireland, annual solar radiation of 3866 MJ/m^2 was assumed [25].

ETSC’s were used in tandem with the main heating system for the generation of hot water for domestic purposes. MCPV panels were used to generate electricity for the pumps, ventilation and lighting requirements of the case study buildings. However, the case study buildings with a building fabric adhering to the 2011 building regulations (i.e. case studies 1 to 4) required a significant amount of additional capacity from the MCPV renewable energy system to achieve an A2 BER. The use of domestic appliances was not accounted for due to the limitations of DEAP [25]. The MCPV system allowed generated electricity not consumed by the case study buildings to be exported back to the electricity grid.

Table 3.11 summarises the differences in the case study buildings in terms of space and water heating systems, system efficiencies and renewable energy technology employed. Energy and GWP intensity values, together with economic costs, for the space and water heating systems, renewable technologies and ventilation methods were sourced from Refs.[170], [247], [282], [265]–[268], [278]–[281]. The EE and EC of the wood stove was not accounted for in the analysis.

Table 3.11: General characteristics of the heating systems and renewable technologies for the eight case studies.

Case Study	Main and *Secondary Heating system	Efficiency Heating System	Renewable Technology	
No.			ETSC (m^2)	MCPV (m^2)
1	Gas boiler and Wood Stove	Main: 91.3%, Sec: 60%	6.46	16

2	Biomass Boiler and Wood Stove	Main: 82.7%, Sec: 60%	6.46	19
3	CHP and Wood Stove	Main: 76% heat & 7% electrical, Sec: 60%	6.46	16
4	Heat pump and Wood Stove	Main: SPF 300%, Sec: 60%	6.46	14
5	Gas boiler	Main: 91.3%, Sec: 60%	6.46	3
6	Biomass Boiler and Wood Stove	Main: 82.7%, Sec: 60%	6.46	4
7	CHP and Wood Stove	Main: 76% heat & 7% electrical, Sec: 60%	6.46	3
8	Heat pump and Wood Stove	Main: SPF 300%, Sec: 60%	6.46	2

Abbreviations

ETSC: Evacuated Tube Solar Collector
MCPV: Multi-crystalline Photovoltaic
SPF: Seasonal Performance Factor
*Secondary heating systems account for 10% of space heating requirements

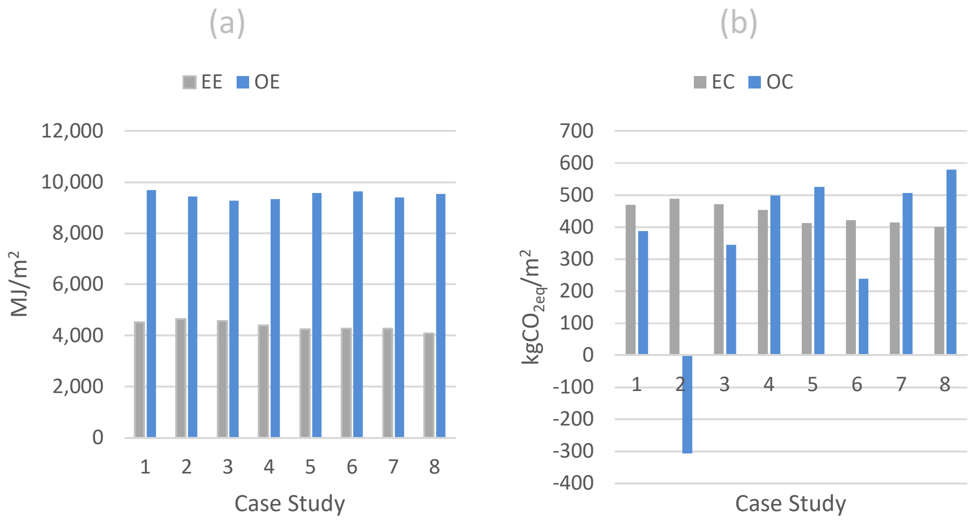
The primary energy conversion factors of electricity, gas and wood pellets were taken as 2.39 MJ_{prim}/MJ_{del} based on the analysis discussed in Section 3.2.7.3, 1.10 MJ_{prim}/MJ_{del} [25] and 1.10 MJ_{prim}/MJ_{del} [25], respectively, throughout the 60-year life cycle of the building. The GWP intensity conversion factors of electricity, gas, and wood pellets were taken as 0.143 $kgCO_2/MJ$ based on the analysis discussed in Section 3.2.7.3, 0.056 $kgCO_2/MJ$ [25] and 0.0069 $kgCO_2/MJ$ [25], respectively, throughout the 60-year life cycle of the building. Using the delivered energy of the respective fuels to each of the case study buildings and current Irish residential energy prices [249], OECs of the case study buildings were determined. 2015 Irish residential electricity, gas and wood pellet prices of 5.77 c/MJ, 1.83 c/MJ and 1.47 c/MJ were assumed for this analysis [249]. Standing charges for energy companies were excluded from the analysis.

3.4.2.1 Life Cycle Energy, GWP and Cost

For the life cycle environmental and life cycle costs presented in this section, it was assumed that emissions and efficiency associated with production of electricity supplied through the mains grid, would remain constant over the lifetime of the building. In addition, static pricing of energy was assumed over the lifetime of the building. The effects of changes to these variables on the hierarchy of the case study buildings, in terms of their environmental and economic impacts over their lifetime, are investigated in Section 3.4.2.4. Furthermore, the results presented in this section did not account for the time value of money, which was considered in Section 3.4.2.2.

Figure 3.8(a)-(c) demonstrates the estimated EE, OE, EC, OC, NCC and OEC of each of the case studies analysed. In terms of EE, super-insulated houses (case studies 5-8) outperformed those with a high level of renewables installed (case studies 1-4). The design with the lowest EE impact was the super insulated house with a heat pump as the main source of heating (case study 8). The design with the highest EE impact was the house using biomass and a large amount of renewables as the main source of heating (case study 2), in addition to having the fourth highest net construction costs. On the other hand, this strategy had the lowest operational cost of all the strategies due to its large installation of renewables. In fact, due to the large amount of MCPV installed, this design exports electricity onto the grid. Assuming an offer of 2.5 c/MJ to export electricity onto the grid [273], this house generated 124 €/yr. Case study 1 and case study 3 were also exporters of electricity. In spite of having a very high efficiency heating system and large installation of renewable energy sources, case study 4 had the second highest operational costs, due to the high cost per MJ of electricity for domestic customers, compared to gas and wood pellets in Ireland [283].

A similar pattern followed for EC, whereby the houses designed to be super-insulated outperformed those with a large installation of renewables. The two houses designed using a biomass boiler (case study 2 and 6) had the lowest OC impact of all the eight designs, due to the low GWP impact of wood pellets. Furthermore, due to the large installation of MCPV in case study 2, 306 $kgCO_2/m^2$ is saved during the building's operational phase.



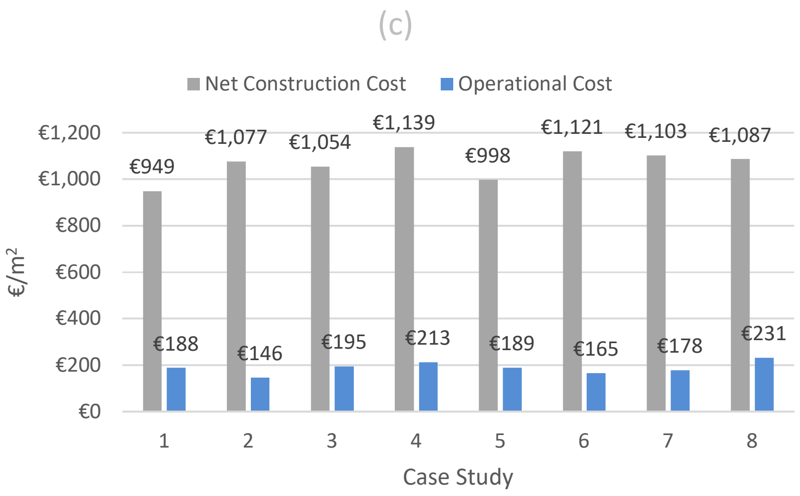


Figure 3.8: (a) Estimated embodied energy (EE) and operational energy (OE), (b) embodied global warming potential (EC) and operational global warming potential (OC), (c) estimated net construction and operational primary energy costs of a typical semi-detached home in Ireland over a 60-year lifespan.

Case study 3 had a GWP impact of 147 $kgCO_2/m^2$ more than the super-insulated house with a biomass boiler (case study 6) during the operational stage. This is 22% of the total amount that case study 6 produced over its lifespan. For the case studies which exported electricity to the grid, the GWP savings were assumed to have the same GWP intensity of the electricity grid for the lifespan of the building (0.143 $kgCO_2/MJ$). In this analysis, the exported electricity was considered avoiding electricity generation. Thus, the GWP and primary energy usage were reduced accordingly and included as part of the use stage of the case study buildings' life cycle assessment (Module B6). Due to the GWP savings associated with the large amount of renewables installed on case studies 1-4, the nZEBs designed to have a large amount of renewables outperformed those which were designed to be super-insulated in terms of OC.

3.4.2.2 Life Cycle Cost-Optimal

Figure 3.9 demonstrates the life cycle cost optimality for each of the analysed case studies from a macroeconomic perspective as described in Section 3.2.5. The design with the lowest life cycle cost was the building with gas as the main source of heating and a large amount of renewables installed (case study 1).

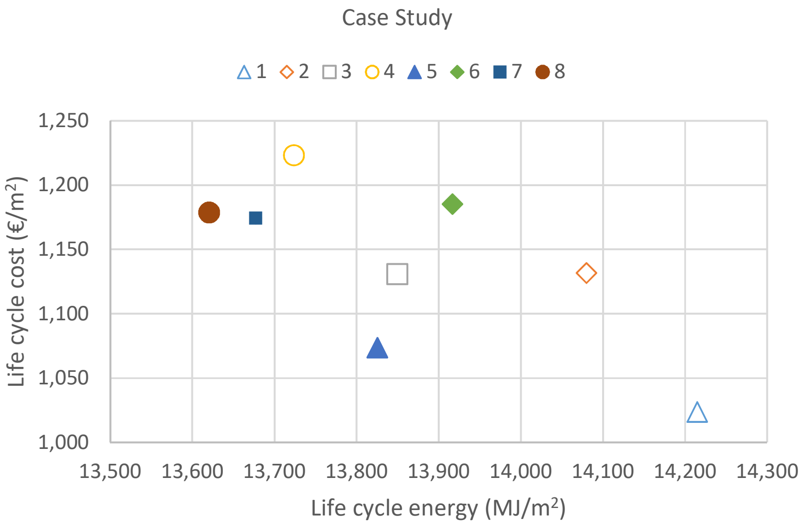


Figure 3.9: Life cycle cost versus life cycle energy of the eight different building designs.

The cost optimal in terms of energy performance is the building designed to be super-insulated with gas as its main heating source (case study 5). Even though case study 8 and 4 had the most efficient heating systems employed (i.e. lowest net secondary energy), the high cost of electricity used by the heat pump resulted in case study 8 and 4 having two of the three highest life cycle costs. The cost of gas was higher than wood pellets, but the efficiency of the gas boiler was greater than that of the biomass boiler resulting in case study 5 being the optimal solution.

3.4.2.3 Sustainability Index Factor

Three of the top four designs in terms of both life cycle GWP and life cycle cost focused their design on having a large amount of renewables installed. Three of the top four designs in terms of life cycle energy focused their design on having a super insulated building. Therefore, each case study had its strengths and weaknesses in terms of life cycle cost, energy and GWP. Thus, using the Sustainable Index Factor (SIF) as described in Section 3.2.6, each of the case studies were evaluated based on economic and environmental indicators evaluated in this analysis. No social indicators were evaluated in this analysis.

The economic indicator (life cycle cost) was given a weighting of one with each of the environmental indicators (life cycle energy and life cycle GWP) given a weighting of

0.5. Both the economic and environmental category were each given a weighting of one with the results shown in Table 3.12.

Table 3.12: SIF impact of the eight case studies.

	Economic		Environmental				
Case Study	Life Cycle Cost		Life Cycle Energy		Life Cycle GWP		SIF
	€/m^2	Impact [-]	MJ/m^2	Impact [-]	kgCO$_{2eq}$/m^2	Impact [-]	[-]
1	1,024	0.90	14,214	1.03	858	1.09	0.98
2	1,132	0.99	14,080	1.02	183	0.23	0.81
3	1,131	0.99	13,849	1.00	816	1.03	1.00
4	1,223	1.07	13,724	0.99	952	1.21	1.09
5	1,074	0.94	13,825	1.00	939	1.19	1.02
6	1,185	1.04	13,917	1.00	661	0.84	0.98
7	1,174	1.03	13,677	0.99	921	1.17	1.05
8	1,179	1.03	13,620	0.98	980	1.24	1.07
Avg.	1140	1.00	13863	1.00	789	1.00	1.00
Std.	65	0.06	203	0.01	265	0.34	0.09

The case study with the lowest SIF impact was case study 2. Based on the cost-optimal methodology, case study 5 was the best solution. However, when using the SIF, which considered only one more category for evaluating the optimal solution, case study 5 was the 5th best design. This is primarily caused by the impact case study 5 had in terms of life cycle GWP. Life cycle GWP experienced the largest variability of the three categories evaluated. This was due to the large variability in the GWP intensity of the fuel sources [25] in addition to the GWP savings achieved by case study 1-3 which were exporters of electricity to the grid due to their large installation of MCPV. For the case studies which export electricity to the grid, the GWP savings were assumed to have the same GWP intensity of the electricity grid.

3.4.2.4 Sensitivity Analysis

Future Irish Electricity Generation Mix

The impact of accounting for changes to the fuel mix for generating Irish electricity to the life cycle GWP and life cycle primary energy usage for each case study is shown in Figure 3.10 and Figure 3.11, respectively.

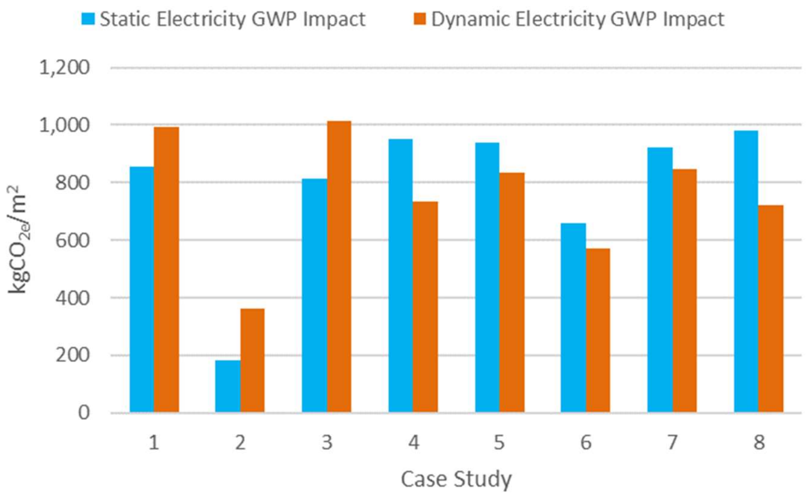


Figure 3.10: Impact of accounting for decarbonisation of electrical grid over 60 years on case studies life cycle GWP.

Changing electricity generation fuel mix resulting in a decarbonised electricity grid and increased energy efficiency had a significant impact on the hierarchy of case studies life cycle GWP and primary energy usage. Case studies 4 and 8 had the highest GWP, assuming a static GWP intensity of electricity generation. Accounting for fuel mix changes resulted in case studies 8 and 4 having the 3rd and 4th lowest life cycle GWP (Figure 3.10).

The biomass boiler with a large amount of renewables design (case study 2) outperformed it super-insulated counterpart (case study 6). For all other case studies, the super-insulated designs outperformed their large renewable energy counterparts due to the minimising impact of the MCPV installation.

Accounting for increasing efficiency of Irish electricity generation, all the super-insulated designs outperformed their large renewable energy counterparts. Case studies 1, 2 and 3 were all electricity exporters to the grid. Due to the diminishing savings of the MCPV in terms of GWP and primary energy caused by the decarbonisation and improved efficiency of the electricity grid, case studies 1-3 had a larger life cycle GWP impact and primary energy usage compared to their static GWP electricity grid intensity and efficiency scenarios.

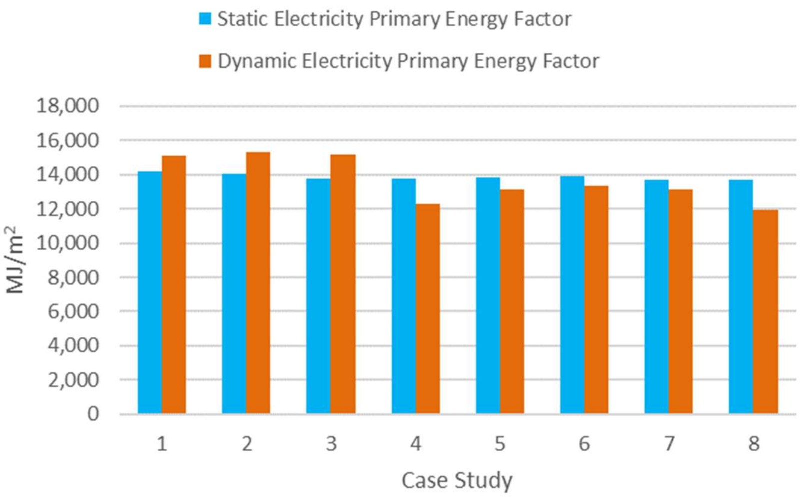


Figure 3.11: Impact of improving electricity grid efficiency over 60 years on case studies' life cycle energy usage.

In fact, as the primary energy factor for the electricity grid improved due to improved generation efficiencies, the impact of exporting electricity to the grid from on-site electricity generation reduced. This resulted in case studies 1, 2 and 3 not achieving the required A2 BER to be considered an nZEB building when annualising their life cycle primary energy usages. They achieved an A3 rating instead, which would meet the current Irish building energy regulation requirements [24]. Of course, this assumed that the efficiency of the on-site generation is constant over the life of the building. All other case studies remained an A2 rated dwelling.

Discount rate

In the case studies' cost optimal results presented in Figure 3.9, the discount rate of 4% is assumed which effects the operating costs of the building. An analysis was done to determine the impact a varying discount rate has on the annual energy costs using the present value of annuity (PVA) formula, with the results given in Figure 3.12. For all discount rates, a building designed with a gas boiler as its main heating system with a large amount of renewable technology (case study 1) or super-insulated (case study 5) had the lowest and second lowest total life cycle cost, respectively.

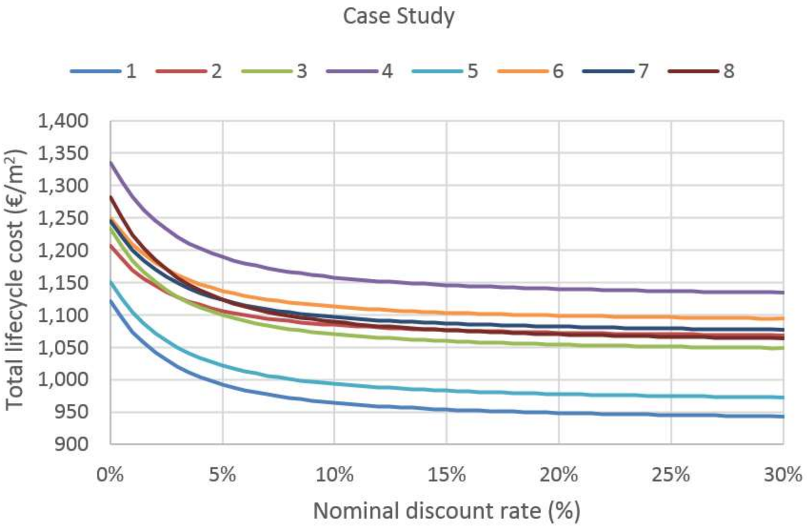


Figure 3.12: Relationship between the total life cycle cost and nominal discount rates for the investigated case study houses.

The Stern Review on the Economics of Climate Change uses a social discount rate for evaluating the economic impact of climate change [284]. The social discount rate is evaluated based on the elasticity of marginal utility of consumption, the growth rate of consumption and the pure time discount rate. The pure time discount rate is based on the probability of existence. Stern argues that the probability of existence for all generations should be equal and that the probability of a catastrophic event is very low. By assuming the probability of a catastrophic event is very low, the discount factor would remain low (i.e. <10%). Therefore, the range of discount rates up to 30% as shown is improbable. Although, a discount rate of greater than 10% does not have any impact on the hierarchy of LCC results in Figure 3.12. In the wider context, for a discount above 10%, people would be more likely to invest their money into high yield investment portfolios rather than measures such as energy retrofitting that help Ireland transition to a decarbonised economy.

Figure 3.13 shows the equivalent annual cost (*EAC*) of constructing and operating the case study buildings at various discount rates, where the operation costs are based on energy usage only. As seen in Figure 3.13, similar to the PVA results, a building designed with gas boiler as its main heating system with a large amount of renewable technology (case study 1) or super-insulated (case study 5) had the lowest and second lowest EAC, respectively.

Energy Costs

For the operational costs given previously (Figure 3.8(c), Figure 3.9, Figure 3.12 and Figure 3.13), energy prices were assumed to remain constant throughout the buildings' lifespan. Table 3.13 compares the AECs of the eight case studies, based on a constant energy price (static pricing) and accounting for increases in energy price using the average annual growth rate in fuel energy prices (dynamic pricing). Prices for exporting electricity back onto the national electricity grid were assumed to remain at 2.5 c/MJ, in both the static and dynamic pricing scenarios [273].

As shown in Table 3.13, the case studies using a biomass boiler as their main heating source had the lowest annual cost over the building's life cycle with static pricing. However, with an assumed annual growth rate of 3.8% in wood pellet prices, these two case studies had the 1st and 4th highest annual cost over the buildings' life cycle. From the cost perspective, the two scenarios involving heat pumps (i.e. case study 4 and 8) remained among the worst options (i.e. ranked 6th and 7th out of 8), and the scenarios involving the condensing gas boilers (i.e. case studies 1 and 4) became the best options.

Life Cycle Cost Optimal

Accounting for increasing energy prices and improvements in the efficiency of the electricity grid, the design with a gas boiler focusing on having a building fabric with high thermal and air-tightness performance (case study 5) remained the cost optimal

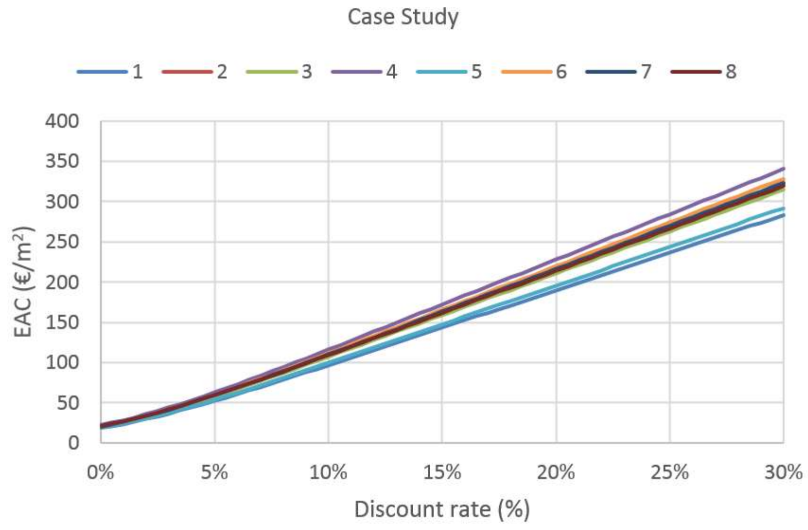


Figure 3.13: Equivalent annual cost (EAC) of constructing and operating the case study buildings at various discount rates (Note: operation costs are based on primary energy usage only).

Table 3.13: Difference in AECs of case studies assuming an annual growth rate in energy prices.

	Static Pricing				Dynamic Pricing			
Case Study	Electricity (€/yr)	Gas (€/yr)	Biomass (€/yr)	Total (€/yr)	Electricity (€/yr)	Gas (€/yr)	Biomass (€/yr)	Total (€/yr)
1	-93	394	31	332	-93	931	114	952
2	-124	0	382	258	-124	0	1394	1270
3	-136	450	31	345	-136	1063	114	1041
4	345	0	31	376	1033	0	114	1147
5	163	168	2	333	488	398	7	893
6	139	0	152	291	418	0	554	971
7	120	192	2	314	361	454	7	822
8	406	0	2	408	1219	0	7	1225
Avg.	102	301	79	332	396	712	289	1040
Std.	208	142	132	47	519	335	481	160

solutions (Figure 3.14). In addition, the differences between the super-insulated designs and their renewable energy counterparts in terms of life cycle costs reduced substantially compared to the results seen in Figure 3.9. Accounting for both increasing energy costs and varying discount rates, the building designed with gas as the main heating system and a large amount of renewables installed (case study 1) and to be super-insulated (cased study 5) remained the best solutions in terms of PAV and EAC.

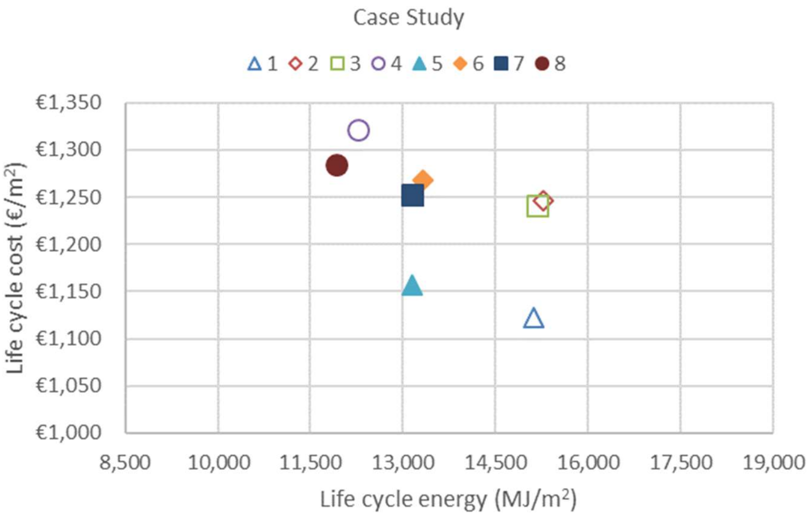


Figure 3.14: Life cycle cost, which accounts for increasing energy costs, versus life cycle energy, which accounts for increasing efficiency of the electricity grid, of the eight different designs.

<u>Sustainability Index Factor</u>

When assuming static energy prices, electricity grid efficiency and electricity grid carbon intensity, three of the designs focusing on renewable technologies out performed their super-insulated design counterparts. Case study 2 had the lowest SIF impact and case study 5 was the cost-optimal solution. However, when using the SIF case study 5 was the 5th best design.

Accounting for increasing energy prices, increasing electricity grid efficiency and grid decarbonisation, all but one of the super-insulated designs outperformed each of their renewable energy focused counterparts in terms of their respective SIF impacts (Table 3.14). The biomass boiler with a large amount of renewables still outperformed its super-insulated counterpart due to its lower GWP impact. Case study 2 still had the lowest SIF impact and case study 5, the cost-optimal solution, had the 4th lowest SIF impact.

Table 3.14: SIF of the eight case studies accounting for increasing energy prices, increasing electricity grid efficiency and grid decarbonisation

	Economic		Environmental					
Case Study	Life Cycle Cost		Life Cycle Energy		Life cycle GWP		SIF	
							Dynamic Scenario	Static Scenario
	€/m^2	Impact [-]	MJ/m^2	Impact [-]	kgCO$_{2eq}$/m^2	Impact [-]	Impact [-]	Impact [-]
1	1123	0.91	15,120	1.11	993	1.31	1.06	0.98
2	1246	1.01	15,283	1.12	363	0.48	0.90	0.81
3	1241	1.00	15,172	1.11	1,013	1.33	1.11	1.00
4	1322	1.07	12,273	0.90	735	0.97	1.00	1.09
5	1157	0.94	13,140	0.96	837	1.10	0.98	1.02
6	1268	1.03	13,329	0.97	573	0.75	0.94	0.98
7	1252	1.01	13,169	0.96	845	1.11	1.03	1.05
8	1284	1.04	11,911	0.87	724	0.95	0.97	1.07
Avg.	1236	1.00	13675	1.00	760	1.00	1.00	1.00
Std.	66	0.05	1344	0.10	216	0.28	0.07	0.09

3.5 Discussion and Conclusion

3.5.1 Impact of Changes in Building Regulations

Environmental and economic LCA analyses on case study semi-detached houses designed to previous and current building energy performance regulations in Ireland was carried out in Section 3.4.1. Case study semi-detached residential buildings designed to varying degrees of operational performance fluctuated in terms of financial requirements and associated EE and EC intensities. The emergence of EE and EC as a dominant construction environmental component is vividly noticeable as the case study building moved towards an nZEB standard. For the house designed to the 2005 building regulations in Ireland (case study 1), the EE and EC contributed 11% and 19% of the building's environmental life cycle impact. For the two nZEB semi-detached case studies (4a and 4b), the EE contribution increased to 33% and 31%, with the EC contribution increasing to 52% and 44%, respectively. As can be seen from the embodied environmental indicators assessed, the materials of nZEB buildings can account for up to a third of the energy demand and a half of the GWP impact of a building over its lifespan. However, with future electricity grid decarbonisation, electricity grid efficiency improvements and depending on the heating system employed, the life cycle EE and EC of the nZEB case studies ranged from 30% to 36% and from 47% to 100%, respectively, as examined in Section 3.4.2.

Therefore, the importance of a designer’s role in selecting sustainable ‘green’ materials is highly stressed. This is particularly important considering EE and EC are initial consumptions and emissions, whereas OE and OC occur over the building’s life cycle.

The superstructure of cavity masonry block wall semi-detached houses with a concrete foundation was the main contributor to the embodied impact of the building. Bricks, blocks and concrete have been the main material choices for the superstructure of buildings in Ireland since pre-1900s [20]. Timber frame houses have become more common in Ireland since the 1990s [20] and light weight steel frame houses are starting to become a superstructure market option for Irish housing [285]. A thorough investigation is required to examine different superstructure design strategies for various building typologies to identify the more sustainable design strategy from an environmental, economic and social standpoint. This research will aid in identifying and mitigating material hotspots for more sustainable Irish building construction. Research on the environmental and economic impact of different superstructure design strategies for an Irish semi-detached building has been carried out [286] but further research is required in this area. Renewable energy technology was found to be a potential hot spot for nZEB building designs. For an nZEB building design focused on a high thermal fabric efficiency design, the heating and renewable technology system contributed to 14% of the energy embodied impact. The embodied impact of the heating and renewable technology system increased to 24% if the nZEB building design focused on having a large amount of renewable technology.

3.5.2 Best Design Strategy for Irish Residential Semi-Detached nZEB

The objective of the analysis presented in Section 3.4.2 was to determine for buildings in a temperate oceanic climate, such as Ireland, if it is better to design an nZEB to be a super-insulated building with minimum heating requirements, or to provide less insulation and air-tightness but install a large amount of renewable energy sources. The case studies involved in the analysis were assessed using two different methodologies to determine the best solutions. The first was the cost-optimal methodology framework which is mandatory in all EU member states for calculating cost optimal levels of minimum energy performance requirements for buildings and building elements [75]. The second was a methodology termed the Sustainability

Index Factor (SIF) that incorporates the commonly known three pillars of sustainability: environmental, social and economic. In the analyses of both methods, account was taken for varying discount rates, future electricity grid de-carbonisation, improved efficiency of the electricity grid and future energy prices.

Based on the SIF methodology using static energy prices and electricity grid efficiency, nZEB residential buildings with a focus on renewable technology outperformed their super-insulated design counterparts apart from the heat pump designed houses. Accounting for increasing energy prices, increasing electricity grid efficiency and electricity grid decarbonisation had a significant impact on the hierarchy of the SIF of the eight case studies. Biomass with a large amount of renewables remained the best option due to its low GWP impact with all other heating system super-insulated designs outperforming each of their renewable energy focused counterparts in terms of their respective SIF impacts. This was primarily due to differences in life cycle costs reducing, the improved efficiency and decarbonisation of the electricity grid, and the resulting diminished energy and GWP savings associated with the MCPV minimising overtime. This suggests that buildings should not be designed to be the exporters of electrical energy to compensate for large use of other forms of energy during their operational phase due to diminishing energy savings over time of renewable electricity.

However, the cost optimal energy performance and SIF results showed different optimum design solutions. The cost optimal results suggested that the super-insulated buildings with a gas boiler (case study 5) to be the cost optimal design. The SIF results showed the biomass boiler with a large amount of renewables (case study 2) and the super-insulated building with a heat pump (case study 8) to have the lowest SIF impact due to evaluating another category in its assessment, GWP.

Choosing the best heating system from an economic perspective is difficult as the hierarchy of the OEC results are dependent on existing fuel prices and the assumptions made with regards to the annual change of energy costs. Predicting future energy prices was difficult due to numerous variables that impact those prices. For instance, a report from the Sustainable Energy Authority of Ireland had predicted a range of scenarios for the trade price of wood pellets across the EU from 2010 to 2030 [287]. From 2010 to 2015, the average EU annual growth rate had been predicted to fall by

4.61% annually. However, in reality, the average annual price of wood pellets in Ireland increased at a growth rate of 5.68% annually for the same period [249]. Thus, the life cycle cost of each of the case studies may vary significantly in the future, compared to what the results suggested in this analysis, and may have a big impact in terms of the hierarchy of which case study is the cost optimal and have the lowest SIF impact. 2015 Irish residential energy prices [249] were used in the analysis of Section 3.4.2, for electricity, gas and wood pellet prices. The cost per kWh of gas and wood pellets were 32% and 25% that of electricity. Given the high efficiency of heat pumps however, if the difference in fuel prices between electricity, gas and wood pellets reduce overtime, heat pumps would become a more cost-effective solution. A householder could also protect themselves against the volatility of future fuel prices by minimising the space heating requirements through a building envelope with high thermal efficiency and air-tightness performance.

Overall, it is believed that more focus should be placed on (i) minimising the space heating requirements through a building envelope with high thermal efficiency and air-tightness performance and (ii) covering the remaining energy demand, to a very significant extent, by renewable sources that compensate for buildings' specific energy source during their operational phase. However, this was based on the evaluation of three indicators for building design. Even accounting for one more indicator (GWP) changed the hierarchy of the optimum designs.

There are many tools already established across Europe for evaluating the sustainability of a building using economic, social and economic indicators, e.g. HQM [250], DNGB Certificate System [251], LiderA [251], SBTool [251], HQE [251] and HPI [252]. However, there is a need for a framework to develop a tool for assessing the sustainability of a building using multiple common categories/indicators for cross comparison in EU countries. Further indicators could be included for the sustainability evaluation depending on the specific circumstances of the building itself. The SIF methodology employed in this study can be used for assessing the SIF impact of a set of buildings which are representative of a country's national building stock for a number of economic, social and environmental indicators.

Based on the three categories evaluated (life cycle cost, life cycle energy and life cycle GWP) using the SIF methodology and accounting for increasing energy prices and increasing electricity grid efficiency, heating systems that have a low impact on the natural environment, such as a biomass boiler or heat pump, should be installed in nZEB residential buildings in Ireland. If the difference between the price of electricity per kWh in comparison to the price of gas and wood pellets per kWh can be reduced and more efficient biomass boilers are installed in residential buildings, heat pumps and biomass boilers would become a more sustainable heating system solution for nZEB residential buildings.

While the case study buildings examined different thermal fabric and heating system design strategies for a new build semi-detached residential building from an environmental and economic perspective, the optimum insulation thicknesses for the building elements from an environmental and economic perspective were not assessed. The results show that it is more effective to increase the thermal performance of building elements from a cost-optimal perspective. It could be argued that as the energy sources used to operate buildings and in the manufacturing of construction materials become decarbonised, there is less of a need for building elements to continue improve their thermal performance as the environmental impacts from the operation of buildings and the materials used to construct the building elements will have been mitigated. However, it is important to continue to improve the thermal performance of building elements to decrease the operational energy demand of buildings as long as it is economically feasible. This is to ensure there is less stress put on the energy generation network and allow the generation network to operate more efficiently.

In summary, the results of the research presented in this chapter find that:

- For new build residential buildings, the interrelationship of the materials used in the construction of the building and the energy demand practices during the operational phase result in the EE and EC of a new build semi-detached building constructed to 2005 energy performance building standards accounting for 11% and 19% of the building's environmental life cycle impact. The EE and EC of a new build residential semi-detached nZEB can account for up to 36% and 100% of its life cycle energy and GWP impacts, respectively. Thus, the importance of a designer's role in sustainably selecting appropriate ‘green’ materials is highly stressed as buildings move towards nZEB standards in Ireland.

- The superstructure of cavity block wall semi-detached houses with a concrete foundation is the main contributor to the embodied impact of the building. A thorough investigation is required to examine different superstructure design strategies to identify and mitigate their material hotspots for more sustainable Irish building construction. Renewable technology is found to be a potential hot spot for nZEB building designs.
- For designing a new build residential semi-detached nZEB, more focus should be placed on (i) minimising the space heating requirements through a building envelope with high thermal and air-tightness performance, and (ii) covering the remaining energy demand, to a very significant extent, by renewable sources that compensate for buildings’ specific energy source during their operational phase.
- Based on (i) the three categories evaluated (life cycle cost, life cycle energy and life cycle GWP), (ii) using the SIF methodology and (iii) accounting for increasing energy prices and electricity grid de-carbonisation and increased efficiency, heating systems that have a low impact on the natural environment, such as a biomass boiler or heat pump, should be installed in nZEB buildings in Ireland.
- There is a need for a more robust assessment methodology for evaluating the sustainability of residential housing, rather than relying on the cost optimal level based on energy performance. The SIF methodology used, can be used for assessing the sustainability of a set of buildings which are representative of a country’s national building stock for a number of economic, social and environmental categories.

Chapter 4. Life Cycle Analysis of Building Energy Efficiency Retrofits

4.1 Introduction

1.9 million housing units in Ireland are required to be retrofitted for the existing Irish national housing stock to be considered nZEB as discussed in Chapter 1. That's 97% of the existing residential housing stock. Semi-detached and terraced houses make up 43% of the existing residential housing stock in Ireland [262]. 1,697,665 housing units in Ireland are occupied with 23% of these being gas heated semi-detached or terraced houses [262]. This chapter examines retrofit packages aimed at improving the material efficiencies and energy demand of gas-heated semi-detached and terraced houses in Ireland. Using both theoretical and monitored case study buildings, the analysis assesses the energy and cost savings associated with material focused energy efficiency retrofits.

However, inaccurate assumptions regarding material and technology performance characteristics and energy demand practices of people have been identified for discrepancies in expected retrofit energy savings. To examine whether social impacts need to start being quantified with economic and environmental indicators in designing and evaluating the sustainability of a residential building energy efficiency retrofit in Ireland, building thermal fabric and heating system retrofit energy efficiency design packages for residential buildings in Ireland are examined in **Chapter 4** incorporating environmental, economic and social indicators. The parameters employed in Chapter 4 to examine the interrelationships between the operational energy demand practices in buildings, the people occupying buildings and the materials and technology used in the retrofit of the buildings are depicted in Figure 4.1.

The chapter is divided into four sections. Section 4.2 describes how the life cycle environmental, life cycle economic and social impacts of the retrofitted case study buildings are determined. Furthermore, the procedure for calculating the cost-optimal levels of minimum energy performance of the case study designs and their SIF impact from a householders and societal perspective are presented. Section 4.3 presents the energy efficiency retrofit packages for the theoretical and monitored case study buildings. In Section 4.4, the optimum energy efficiency retrofit packages for the theoretical case study building are presented. Additionally, the role householder's energy consumption plays in the success of an energy retrofit in reducing the energy consumption of a set monitored co-operative social housing units is presented. Finally, Section 4.5 discusses the need to move away from operational energy and life cycle cost as the only indicators in assessing the success of an energy efficiency retrofit to a method that encompasses multiple environmental, economic and social indicators.

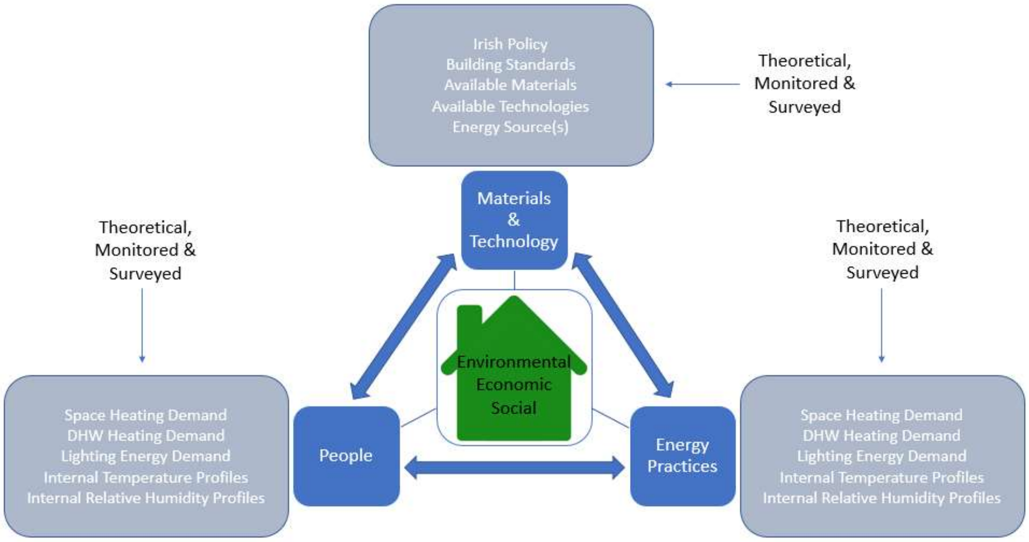


Figure 4.1: The parameters employed in Chapter 4 to examine how the interrelationships between the operational energy demand practices in buildings, the people occupying buildings and the materials and technology used in a building retrofit influence the environmental, economic and social impact of building retrofits.

4.2 Methodology

In Ireland, any residential building undergoing retrofit energy efficiency works to more than 25% of its surface area will be required to be retrofitted to an nZEB standard from September 2019 [28]. To be considered an nZEB retrofit, a residential building must achieve a minimum energy performance of 125 kWh/m^2/yr. However, if a minimum energy performance of 125 kWh/m^2/yr is found to be cost-optimally unfeasible, a cost-optimal retrofit design solution that does not achieve an energy performance of 125 kWh/m^2/yr may be used instead.

Both the cost-optimal methodology framework [75] and the SIF framework presented in Chapter 3 are used in this chapter to assess the optimum energy efficiency retrofit packages from 35 different packages for a residential building from both a customer/householder perspective and from a societal perspective. The cost-optimal methodology and SIF framework are then used to assess an energy efficiency retrofit package applied to a group of monitored residential case study buildings in Ireland.

4.2.1 Material Production Stage (Module A1-A3)

Life cycle environmental indicators are used to evaluate the environmental impacts of energy efficiency retrofit designs. The standards for building LCA calculation require the boundary for refurbishment/retrofit (Module B5) to include (i) the production of new building components, (ii) transportation of new building components, (iii) construction as part of the refurbishment process, (iv) waste management and (v) end of life of the replaced components [30]. The production of new building components and their impact on the operation energy use of the building are the most common boundaries assessed in LCA retrofit studies [154]. Oregi et al. [288] examined the relevance of each life cycle stage in relation to building retrofit and found the transportation and end of life stages to be minor [288]. Famuyibo et al. [176] found that the maintenance and disassembly stages for retrofitting a residential building in Ireland to passive standards accounted for at most 3.7% and 0.9% of the building's environmental LCA, respectively [176].

In the analysis presented in this chapter, the production of new building components (Module A1-A3) and their impact on the building operational energy use (Module B6) are assessed. Environmental intensities of materials/products are sourced from environmental product declarations (EPDs) or Ecoinvent (v3.4) [256]. EPDs are sourced from multiple available online databases [289]–[291]. The Irish EPD platform is the default online EPD database used in this study [289]. If an EPD is unavailable on the Irish EPD platform, other online databases are used [290], [291]. If EPDs are unable to be sourced for a material/product, environmental intensities are sourced from Ecoinvent (v3.4) [256]. The method outlined in Section 3.2.1 is used to assess the environmental impacts from the production of building components used in the retrofit. However, it should be noted that the environmental intensity database used for the analyses in this chapter is different than that used in Chapter 3, as access to Ecoinvent (v3.4) [256] was not available when completing Chapter 3, which has been published in two journal papers ([32], [36]). A breakdown of the environmental embodied intensities of the materials used for the energy efficiency retrofit materials/products and their source is given in Appendix B.

From the review of retrofit studies presented in Section 2.3, it was found that energy and GWP (also referred to as greenhouse gas emissions and climate change) are the most common environmental indicators in LCA studies. Eutrophication potential (EP), acidification potential (AP) and ozone depletion potential (ODP) are also often used. The EU recently published guidelines on sustainability indictors for office and residential buildings that include using LCA [42]. The guidelines recommend using GWP, ODP, AP, EP, photochemical ozone creation potential (POCP), abiotic depletion potential of elements (ADPE) and abiotic depletion potential fossil fuels (ADPF). These are also the mandatory impact categories that must be included in an impact assessment of a product to be included in the EPD Ireland programme [292]. Other optional impact categories may be included on the EPD certificate in the EPD Ireland programme in order to allow validity in other jurisdictions, such as human-toxicological effects, eco toxicological effects (aquatic - fresh water, aquatic - sea water and terrestrial), air pollution and water pollution [292].

This analysis uses energy, GWP, OCP, AP, EP and POCP as environmental indicators. These indicators will change during a building's life cycle due to Irish electricity grid decarbonisation, as discussed in Section 3.2.7.3. ADPE and ADPF are measures of the scarcity of a substance, which depends on the amount of resources and extraction rate [293]. As it is not possible to predict how the amount of resources and extraction rate changes due to grid decarbonisation, ADPE and ADPF are not included in this analysis.

4.2.2 Use Stage: Building Operation (Module B6)

Annual operational secondary energy and the energy savings from the examined retrofit packages are estimated using DEAP [25]. The environmental impact per MJ_{del} of electricity, gas and coal are taken from Ecoinvent (v3.4) [256]. The environmental impact of the building's operational energy use is determined using Equation 3.5, where the estimated operational secondary energy use is estimated from DEAP and the fuel environmental impacts from Ecoinvent (v3.4) [256].

Changes to the future fuel mix for Irish electricity generation over the lifespan of the retrofit were considered in the study. The environmental energy, GWP, OCP, AP, EP and POCP intensities of the Irish electricity grid were used based on the results and analysis of Section 3.2.7.3.

4.2.3 Net Construction Costs

The external wall EPS insulation and cavity wall beaded EPS insulation material and labour costs are sourced from an insulation supplier [294].The Tabula project assessed basic and advanced retrofit steps to improve the energy efficiency of Irish residential buildings [20]. The costs of material and labour for the roof insulation energy efficiency retrofit measures are taken from the Tabula project. For the price of rock wool insulation, the material costs are sourced from an insulation price guide [295]. For the cost of labour for installing the rock wool insulation, the cost of labour for installing the mineral wool insulation is used. The cost of labour for installing the mineral wool insulation is assumed to be the difference in the material cost of mineral wool insulation from the insulation price guide [295] and the cost of material and labour from the Tabula project [20].

For the window and door costs, Tabula only provides a cost/m^2 for different window and door U-values. However, a price for windows and doors with a U-value of 0.7 W/m^{2}K is not included in the Tabula document [20]. In addition, the cost of a window and door depends on multiple factors including frame design, frame size, and material. As such, costs for the manufacturing and installation of windows and doors are instead sourced from Munster Joinery [296].

Costs for the materials and labour of upgrading the heating system and the installation of renewable technology are sourced from the heating system energy efficiency measures applied to the monitored case studies discussed later in Section 4.3.2, a building contractor [297], a heat pump supplier[298], a solar PV supplier [299] and the Tabula project [20].

4.2.4 Operational Economic Costs

Annual operational primary energy and the energy savings from the examined retrofit packages are estimated using DEAP [25]. A life span of 30 years is assumed in this analysis. 2015 energy prices for electricity, gas and coal [249] are used with the operational energy demand estimated from DEAP to determine the operational economic costs and savings for the retrofit solutions. As required in the cost-optimal methodology [16], the operational costs account for future energy price scenarios. The price of electricity, gas and coal in Ireland is sourced every year dating back to 1990 [249]. The Irish energy market experienced price increases and decreases over the past three decades with the increases outweighing the decreases. Residential electricity prices grew by an annual average growth rate of 3.0% between 1990 and 2018. Residential gas and coal prices grew by annual average growth rates of 2.7% and 3.3%, respectively. It is assumed that Irish fuel energy prices will experience the same annual growth rates into the future in this analysis.

4.2.5 Cost-Optimal Methodology Framework

The cost-optimal methodology framework for calculating cost optimal levels of minimum energy performance requirements for buildings and building elements [16] is used in this analysis to determine the cost-optimal solution from both a householder perspective and a societal perspective. However, the embodied energy of the materials invested into a building is accounted for in the current study despite not being required as part of the cost-optimal methodology framework set out by the EPBD. Refer to Section 3.2.5 for further details on how the life cycle costing of cost-optimal methodology framework is determined.

When examining the LCC of a retrofit package from a customer/householder perspective, all grant subsidies and applicable taxes including VAT and charges should be taken into account [75]. In this analysis, a VAT rate of 13.5% is applied to building materials, labour costs and energy prices. Standing charges for energy companies are excluded.

When examining the LCC of a retrofit package from a macroeconomic/societal perspective, all grant subsidies and applicable taxes including VAT and charges should be excluded and a new cost category cost of carbon should be included [75].

Ireland is facing fines from the EU if it does not meet energy efficiency and carbon reduction targets by 2020 and beyond to 2030 [254]. Instead of paying fines, the Irish government are investing in building energy efficiency retrofit measures to achieve energy and carbon reduction targets by offering grants to householders. Multiple grant programmes are offered by SEAI to householders to encourage investment in energy efficiency retrofit measures [300]. Current SEAI grants available to householders and to householders as part of the SEAI Better Energy Communities Scheme are given in Table 4.1 and Table 4.2, respectively. In this analysis, grant subsidies are taken account of from both the householder and societal perspective, as the government will have to pay fines if energy efficiency and carbon reduction targets are not met.

Table 4.1: Retrofit energy efficiency grants available to householders in Ireland from SEAI [300].

SEAI Better Energy Grants	
Thermal Fabric	Grant
Attic	€400
Cavity Wall	€400
Semi-Detached Internal Dry lining	€2200
Semi-Detached External Insulation	€4500
Heating System	Grant
Air to Water Heat Pump	€3500
Heating Controls	€700
Renewable Technologies	Grant
Solar Thermal	€1200
PV (per kWp installed)	€700

Table 4.2 Maximum available funding levels available to homes as part of the Better Energy Communities Scheme [301].

Home Type	Funding levels for each component
Private Energy Poor	Up to 80%
Private Non-Energy Poor	Up to 35%
Local Authority Homes	Up to 35%
Housing Association Homes	Up to 50% (Maximum 25% of homes may be fuel poor)
Deep Retrofit (BER A3)	Additional 15%

The cost per tonne of carbon produced by a building is assumed to be that used in the study carried out to determine the cost-optimal nZEB energy performance standards for residential buildings in Ireland [76]. As the analysis in the study for determining the nZEB energy performance standards is for 30 years, the cost per tonne of carbon in the final year of their analysis is assumed to remain constant for the remaining 30 years of this analysis. This cost per tonne of carbon is also applied in the householder perspective scenario, as Irish energy customers pay a carbon tax depending on their energy usage.

A discount rate of 4% is applied for both the householder and societal scenarios. The costs associated with maintaining/repairing a building and recycling/selling/disposing of materials/systems are not considered in the life cycle cost analysis, as they are excluded from the life cycle environmental analysis. The standing charges for energy companies are excluded from the analysis in both the householder and societal scenarios.

4.2.6 Sustainability Index Factor

This study examines the impact of the residential retrofit packages using six life cycle environmental indicators, life cycle cost and one social indicator. To be able to examine the trade-offs between multiple indicators from a householder and societal perspective, this analysis uses the SIF previously used to assess the sustainability of new build nZEB residential buildings in Chapter 3.

Characteristics of thermal comfort (operative temperature, humidity, air velocity, etc.), indoor air quality, acoustics and visual comfort can be used to represent the comfort of building occupants. In the EU published guidelines on sustainability indictors for office and residential buildings, the amount of time the operative temperature of a building falls underneath the recommended thermal comfort range is recommended as a healthy and comfortable space indicator [42]. The guidelines also suggest assessing other thermal environment categories according to EN 15251 depending on the building occupant's satisfaction levels. In this analysis, the impact of an energy efficiency retrofit on the thermal comfort of a building occupant, in terms of indoor temperature and relative humidity (RH), is used as the social indicator. Both indoor temperature and humidity have been linked to cardiorespiratory mortality/morbidity [302]. The amount of time the operative temperature of a building falls within the recommended temperature and RH thermal comfort range of a naturally ventilated residential building by EN 15251 [303] is used to represent the social impact the energy efficiency retrofit has on a building occupant. For the operative temperature, the temperature is to be within 18-27°C to be inside the thermal comfort range [303]. The RH must be within 20-70% to be within the thermal comfort range according to EN 15251 [303].

The SIF can have different weightings applied to the economic, environmental or social categories and a different weighting applied to the indicators of each category. In both the householder and societal perspective scenarios, the two social indicators are given an equal rating of 0.5. In both the householder and societal perspective scenarios, there is only one economic indicator considered in this study which is given a weighting of one (Table 4.3). The economic and social categories are given an equal weighting of one.

LCC is used as the economic indicator in the SIF. The LCC calculated from the householder's perspective as part of the cost-optimal methodology is used in the SIF householder's perspective scenario. The LCC calculated from a societal perspective as part of the cost-optimal methodology is used in the SIF societal perspective scenario.

From a householder perspective, a householder is likely to place the most importance on the energy demand of the house, as this is what their energy bills are primarily based on. In the householder scenario, energy is given a weighting of one and the other environmental indicators are ignored. The environmental category is given the same weighting as the economic and social category.

From a societal perspective, most building retrofit environmental policy targets are related to energy and/or carbon. In this study, both energy and GWP are given a weighting of 0.25. The remaining four environmental indicators are given an equal weighting of 0.125. The environmental category is given the same weighting as the economic and social category.

Table 4.3: Category and indicator weightings for the householder and societal scenarios assessed using the SIF.

Category	Economic	Environmental						Social	
Householder	1	1						1	
Societal	1	1						1	
Indicator	LCC	Energy	GWP	ODP	AP	EP	POCP	Temperature	RH
Householder	1	1	0	0	0	0	0	0.5	0.5
Societal	1	0.25	0.25	0.125	0.125	0.125	0.125	0.5	0.5
Abbreviations									
AP: Acidification Potential EN: Energy EP: Eutrophication Potential GWP: Global Warming Potential				LCC: Life Cycle Cost ODP: Ozone Depletion Potential POCP: Photochemical Ozone Creation Potential					

4.3 Case Study Buildings

4.3.1 Theoretical Case Study Building

The cost-optimal methodology and SIF framework are both used to assess the optimum retrofit solutions for retrofitting a theoretical typical 3-bed semi-detached residential house in Ireland. The theoretical case study building employed in this chapter is that presented in Section 3.3.

To examine the cost-optimal methodology for retrofitting cavity wall construction in Ireland against the results of the SIF, basic and advanced thermal fabric and heating systems retrofit energy efficiency solutions were examined. The theoretical case study building was assumed to have thermal fabric efficiencies which meet the 1991 and 1997 Irish building element thermal fabric efficiency standards pre-retrofit [304], [305]. The U-values of the building elements before the retrofit and target U-values for basic and advanced thermal fabric retrofit packages are shown in Table 4.4.

Table 4.4: U-values (W/m^{2}K) of existing building elements and target U-values for basic and advanced retrofit packages.

	Pre-	Post-Retrofit	
Building Element	Retrofit	Basic	Advanced
Roof	0.36	0.10	0.10
Windows	2.8	1.5	0.7
Doors	3.1	1.5	0.7
Wall	0.46	0.33	0.15
Floor	0.43	Existing	Existing

The retrofit process was split into steps, as summarised in Table 4.5. Each step builds upon the previous. The steps were laid out to allow the retrofit to be completed over an extended period. The order of retrofit steps was similar to the Irish Tabula retrofit guide [306]. The impact of each step on the energy demand in the case study building was calculated using the DEAP software. Retrofitting of ground floors is often omitted due to the financial cost of removing and replacing the existing ground floors [188], [307], [308]. Therefore, energy saving measures for the ground floor of the house were not considered in this analysis. The final step involved the addition of renewable energy technology to achieve the newly proposed nZEB building regulations for new residential buildings. The regulations require new buildings to achieve an energy performance coefficient (EPC) of less than 0.3 and a carbon performance coefficient (CPC) of less than 0.35 [28].

Table 4.5: Retrofit steps applied to building.

Step	Action
0	Existing Building
1	Roof Insulation
2	Window & Door Replacement
3	Wall Insulation
4	Heating System
5	Renewable Energy Technology

The basic thermal fabric retrofit solutions are typical retrofit measures applied to building elements in cavity wall houses in Ireland [306]. The basic thermal fabric measures consisted of insulation on the joists of the roof construction, double uPVC glazed-windows and the cavity wall air-gap pumped with bead insulation. The basic heating system retrofit measure involved replacing the existing heating system with a highly efficient gas boiler or air source heat pump (ASHP).

The advanced thermal fabric retrofit measures were designed to surpass building element thermal fabric efficiencies for passive houses. Energy saving measures for attics are limited as the solution is generally to insulate in between and above the joists of the roof if the attic is unheated or insulate in between and below the rafters of the roof if the attic is heated. The basic measure employed for retrofitting the roof achieved a U-value greater than passive standards. The measure was kept the same for the advanced roof retrofit solution. For the windows and doors, the advanced retrofit measures included either uPVC triple glazed windows and doors or Aluclad triple glazed windows and doors that achieved U-values of 0.7 W/m^{2}K.

For cavity walls with an existing airgap in the cavity, the first step always requires pumping the existing air cavity. This is to avoid thermal looping in the cavity if external or internal insulation is applied to the exterior or interior of the wall [309]. Following, there are many trade-offs between the methods for improving the thermal efficiency of exterior walls. A comparative study assessing the effect of insulating an exterior wall internally and externally established that external insulation outperforms the internal insulation configuration by approximately 18% for energy savings [310]. However, when the cost is taken into account the internal insulation requires approximately 50% less investment than external insulation [310]. Therefore, solutions involving either external wall insulation or internal wall insulation were assessed in this analysis.

Renewable energy technology was employed to achieve the newly proposed nZEB building regulations for new residential buildings that will come into effect from April 2019 in Ireland. If the heating system was based on gas central heating, a combination of an evacuated solar tube collector (ETSC) and multi-crystalline photovoltaic (MCPV) system was used. If an air source heat pump (ASHP) was installed, a photovoltaic system was used. The basic and advanced thermal fabric and heating system solutions employed are summarised in Table 4.6 and Additionally, typical fabric insulation products such as expanded polystyrene (EPS), polyethylene and fibreglass have varying environmental impacts [171]. 'Greener' measures for the external wall and attic insulation were also assessed in the analysis. A matrix of the retrofit packages assessed is shown in Table 4.8. 35 different retrofit packages across five case study building are assessed. A more detailed description of the existing building elements and heating system and the energy efficiency retrofit measures for each case study building is given in Table 4.9.

The existing original theoretical case study building was assumed to have an air permeability of $10m^3/(hr.m^2)$. Houses that were (i) classified as receiving grant support on the SEAI DEAP database [311], (ii) have had an air-tightness test complete and (iii) achieved a BER of B1 or B2 achieved an average air permeability of

Table 4.7, respectively.

Table 4.6: Basic thermal fabric and basic and advanced heating system retrofit measures.

Fabric	Basic			
Heating System	Basic		ADV	
Roof	JO	JO	JO	JO
Windows & Door	DG	DG	DG	DG
Wall	CW	CW	CW	CW
Heating System*	GB	ASHP	GB	ASHP
Renewable Technology			ETSC & MCPV	MCPV

Abbreviations	
ADV: Advanced Retrofit Measure ASHP: Air Source Heat Pump CW: Pumped Cavity Wall Insulation DG: uPVC double glazed windows and uPVC doors ETSC: Evacuated Tube Solar Collector EWI: External Wall Insulation GB: Gas boiler	IWI: Internal Wall Insulation JO: Insulation on Joists of Roof MCPV: Multi-Crystalline Photovoltaic TG: uPVC Triple Glazed Windows and uPVC Doors *Includes Hot Water Tank and Heating Controls

Additionally, typical fabric insulation products such as expanded polystyrene (EPS), polyethylene and fibreglass have varying environmental impacts [171]. 'Greener' measures for the external wall and attic insulation were also assessed in the analysis. A matrix of the retrofit packages assessed is shown in Table 4.8. 35 different retrofit packages across five case study building are assessed. A more detailed description of the existing building elements and heating system and the energy efficiency retrofit measures for each case study building is given in Table 4.9.

The existing original theoretical case study building was assumed to have an air permeability of 10m^3/(hr.m^2). Houses that were (i) classified as receiving grant support on the SEAI DEAP database [311], (ii) have had an air-tightness test complete and (iii) achieved a BER of B1 or B2 achieved an average air permeability of

Table 4.7: Advanced thermal fabric and basic and advanced heating system retrofit measures.

Fabric	ADV							
Heating System	Basic				ADV			
Roof	JO	JO	JO	JO	JO	JO	JO	JO
Windows & Door	TG	TG	TG	TG	TG	TG	TG	TG
Wall	CW & EWI	CW & IWI	CW & EWI	CW & IWI	CW & EWI	CW & IWI	CW & EWI	CW & IWI
Heating System*	GB	GB	ASHP	ASHP	GB	GB	ASHP	ASHP
Renewable Technology					ETSC & MCPV	ETSC & MCPV	MCPV	MCPV

Abbreviations

ADV: Advanced Retrofit Measure
ASHP: Air Source Heat Pump
CW: Pumped Cavity Wall Insulation
DG: uPVC double glazed windows and uPVC doors
ETSC: Evacuated Tube Solar Collector
EWI: External Wall Insulation
GB: Gas boiler
IWI: Internal Wall Insulation
JO: Insulation on Joists of Roof
MCPV: Multi-Crystalline Photovoltaic
TG: uPVC Triple Glazed Windows and uPVC Doors
*Includes Hot Water Tank and Heating Controls

Table 4.8: Matrix of retrofit packages applied to the theoretical case study building. Refer to Table 4.5, Table 4.6, Additionally, typical fabric insulation products such as expanded polystyrene (EPS), polyethylene and fibreglass have varying environmental impacts [171]. 'Greener' measures for the external wall and attic insulation were also assessed in the analysis. A matrix of the retrofit packages assessed is shown in Table 4.8. 35 different retrofit packages across five case study building are assessed. A more detailed description of the existing building elements and heating system and the energy efficiency retrofit measures for each case study building is given in Table 4.9.

The existing original theoretical case study building was assumed to have an air permeability of 10m3/(hr.m2). Houses that were (i) classified as receiving grant support on the SEAI DEAP database [311], (ii) have had an air-tightness test complete and (iii) achieved a BER of B1 or B2 achieved an average air permeability of 3.9m^3/(hr.m^2). Houses that achieved BER of B3 or C1 achieved an average air permeability of 8.6m^3/(hr.m^2). In this analysis after completing step 3 for the basic retrofit of the thermal fabric (Retrofit Package A), the building achieved a C1 BER and was assumed to have an air permeability of 7m^3/(hr.m^2). After completing step 3 for the more advanced upgrade of the thermal fabric (Retrofit Packages B-E), the building achieved a B1 BER and was assumed to have an air permeability of 5m^3/(hr.m^2).

Table 4.7 *and Table 4.9 for the retrofit steps and measures applied.*

Retrofit Package /Step	S0	S1	S2	S3	S4(a)	S4(b)	S5(a)	S5(b)
A	EXT	BAS	BAS	BAS	BAS-Gas	BAS-ASHP	ADV-Gas	ADV-ASHP
B	EXT	BAS	ADV-PVC	ADV-EWI	BAS-Gas	BAS-ASHP	ADV-Gas	ADV-ASHP
C	EXT	BAS	ADV-ALU	ADV-IWI	BAS-Gas	BAS-ASHP	ADV-Gas	ADV-ASHP
D	EXT	BAS-G	ADV-PVC	ADV-EWI-G	BAS-Gas	BAS-ASHP	ADV-Gas	ADV-ASHP
E	EXT	BAS-G	ADV-ALU	ADV-IWI	BAS-Gas	BAS-ASHP	ADV-Gas	ADV-ASHP

Abbreviations

ADV: Advanced Retrofit Measure
ALU: Aluclad Window and Door Measure
IWT-Internal Wall Insulation
ASHP: Air Source Heat Pump
BAS: Basic Retrofit Measure
EWI-External Wall Insulation
EXT: Existing Building
G: Green Insulation Measure
PVC: PVC Window and Door Measure

Table 4.9: Detailed description of the retrofit solutions and their associated U-values (W/m^{2}K) for each of the five case study buildings.

Description	Retrofit Package Design	U-Value
S1: Roof Insulation		
Existing: Domestic 30° pitched tiled roof, 2mm breathable felt, batons (35x35mm), rafters (44x175mm), joists (44x225mm), 100mm fibreglass insulation (λ=0.04W/mK), 13mm plasterboard ceiling.		0.356
Retrofit Measures:		
300mm mineral wool insulation (λ=0.04W/mK) applied in between and above joists of roof	A, B, C	0.103

300mm rockwool insulation (λ=0.04W/mK) applied in between and above joists of roof	D, E	0.103
S2: Window and Door Replacement		
Existing: Double glazed uPVC windows (U-value: 3 W/m^{2}k) and uPVC doors (U-value: 3.1 W/m^{2}k)		
Retrofit Measures:		
Double glazed uPVC windows & uPVC doors	A	1.5
Triple glazed passive uPVC windows & uPVC doors	B, D	0.7
Triple glazed passive Aluclad windows & Aluclad doors	C, E	0.7
S3: Wall Insulation		
Existing: Cavity block wall,19mm external plaster, 100mm concrete block, 35mm Air Cavity, 65mm cavity rigid board insulation (λ=0.04W/mK), 100mm concrete block, 12.5mm scratch coat, 5mm gypsum coat, 3 layers of water-based paint either side.		0.459
Retrofit Measures:		
35mm polystyrene bead cavity fill insulation (λ=0.035W/mK)	A	0.343
9mm external render (λ=0.57W/mK), 170mm external EPS insulation (λ=0.037W/mK) and 35mm polystyrene bead cavity fill insulation (λ=0.035W/mK)	B	0.150
35mm polystyrene bead cavity fill insulation (λ=0.035W/mK), 90mm internal wall phenolic insulation (λ=0.021W/mK), 12.5mm plasterboard (λ=0.19W/mK) 3mm gypsum coat (λ=0.05W/mK)	C, E	0.153
9mm external render (λ=0.57W/mK), 180mm external wood fibre insulation (λ=0.04W/mK), 35mm polystyrene bead cavity fill insulation (λ=0.035W/mK)	D	0.151
S4: Heating System		
Existing: Gas fired boiler with an efficiency of 77%. Solid fuel open fire with an efficiency of 30%. Natural ventilation used throughout.		
Retrofit Measures – Option (a):		
Main Space and Water Heating – Gas boiler with efficiency of 92% and hot water tank, Secondary Space Heating- Electric fire heater with 100% efficiency and chimney sealed	A, B, C, D, E	
Retrofit Measures – Option (b):		
Main Space and Water Heating – Air to water (ATW) heat pump with efficiency of 397% and hot water tank, Secondary Space Heating- Electric fire heater with 100% efficiency and chimney sealed	A, B, C, D, E	

Table 4.9: *Detailed description of the retrofit solutions and their associated U-values (W/m^{2}K) for each of the five case study buildings (continued).*

Description	Retrofit Package Design	U-Value
S5: Renewable Energy Technology		
Retrofit Measures – Option (a):		
3.2m^2 evacuated solar tube collector (0.727 zero loss collector efficiency) & 20.4m^2 of photovoltaic panels (3.6kWp)	A	
3.2m^2 evacuated solar tube collector & 13.6m^2 of photovoltaic panels (2.4kWp)	B, C, D, E	
Retrofit Measures – Option (b):		
15.3m^2 of photovoltaic panels (2.7kWp)	A	
10.2m^2 of photovoltaic panels. (1.8kWp)	B, C, D, E	

4.3.2 Monitored Case Study Buildings

A set of Irish residential houses which underwent a material focused energy efficiency retrofit in 2015 were monitored to assess the impact the retrofit had on the energy consumption, internal environment (temperature and relative humidity) and people occupying the buildings. The houses involved in the study are from a co-operative social housing estate in Dublin, Ireland. The houses underwent an energy efficiency retrofit that was funded by a combination of a grant from the Sustainable Energy Authority of Ireland (SEAI) Better Energy Communities grant programme [301] and a rent increase for the householders. The houses are managed by Co-operative Housing Ireland, which is the national federation for the co-operative housing sector.

There were five main types of houses within the study, as defined by construction year and terrace position (figure in brackets indicates the number of houses in category): 1994 mid-terrace (4), 1994 end-terrace (7), 2000 mid-terrace (5), 2000 end-terrace (4) and 2000 semi-detached (3) (See Figure 4.2 to Figure 4.5).

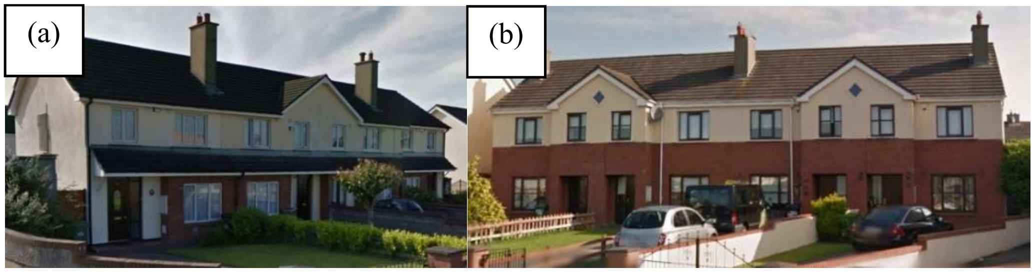


Figure 4.2: (a) 1994 end- and mid-terrace housing and (b) 2000 end- and mid-terrace housing.

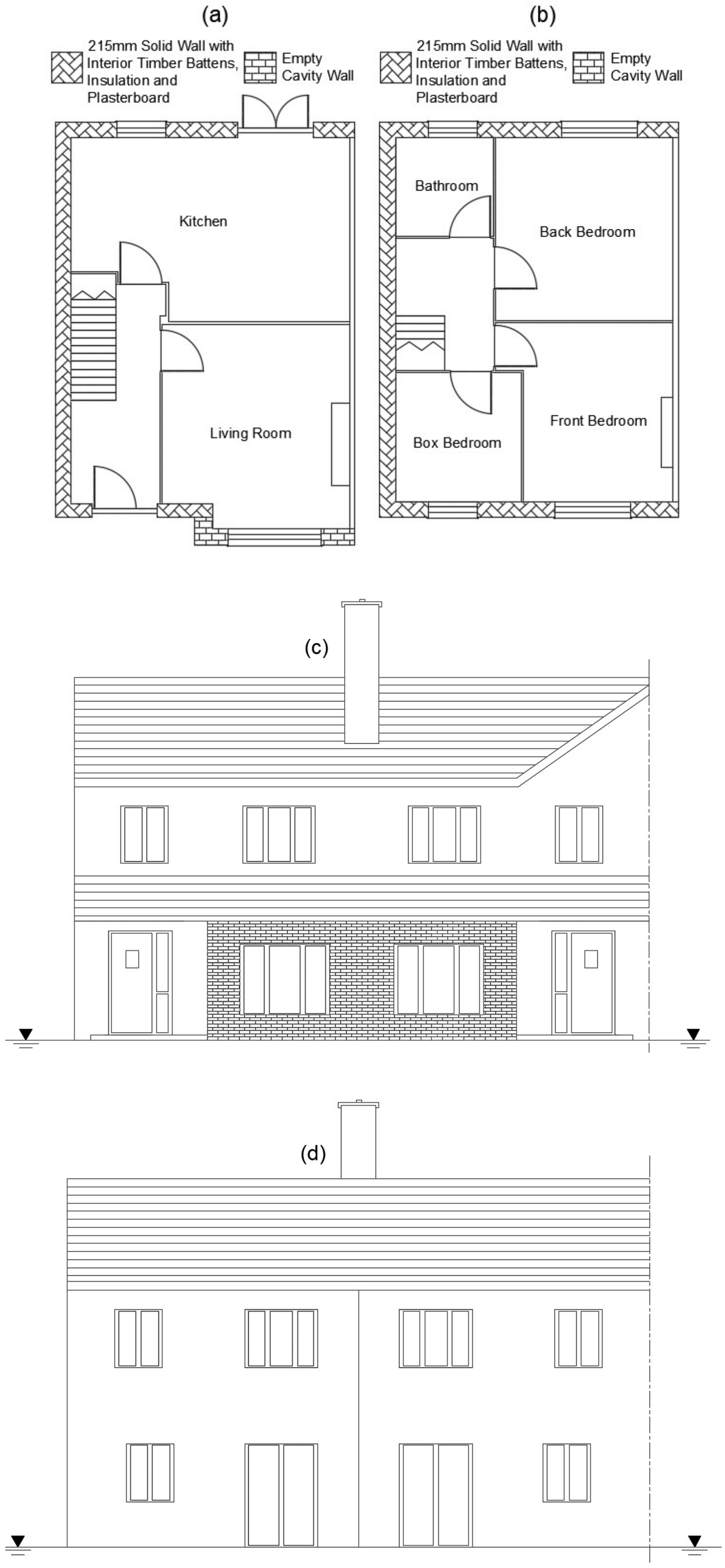


Figure 4.3: (a) Ground floor layout, (b) First floor layout, (c) Front façade and (d) Back façade of the 1994 mid- and end-terrace case study building.

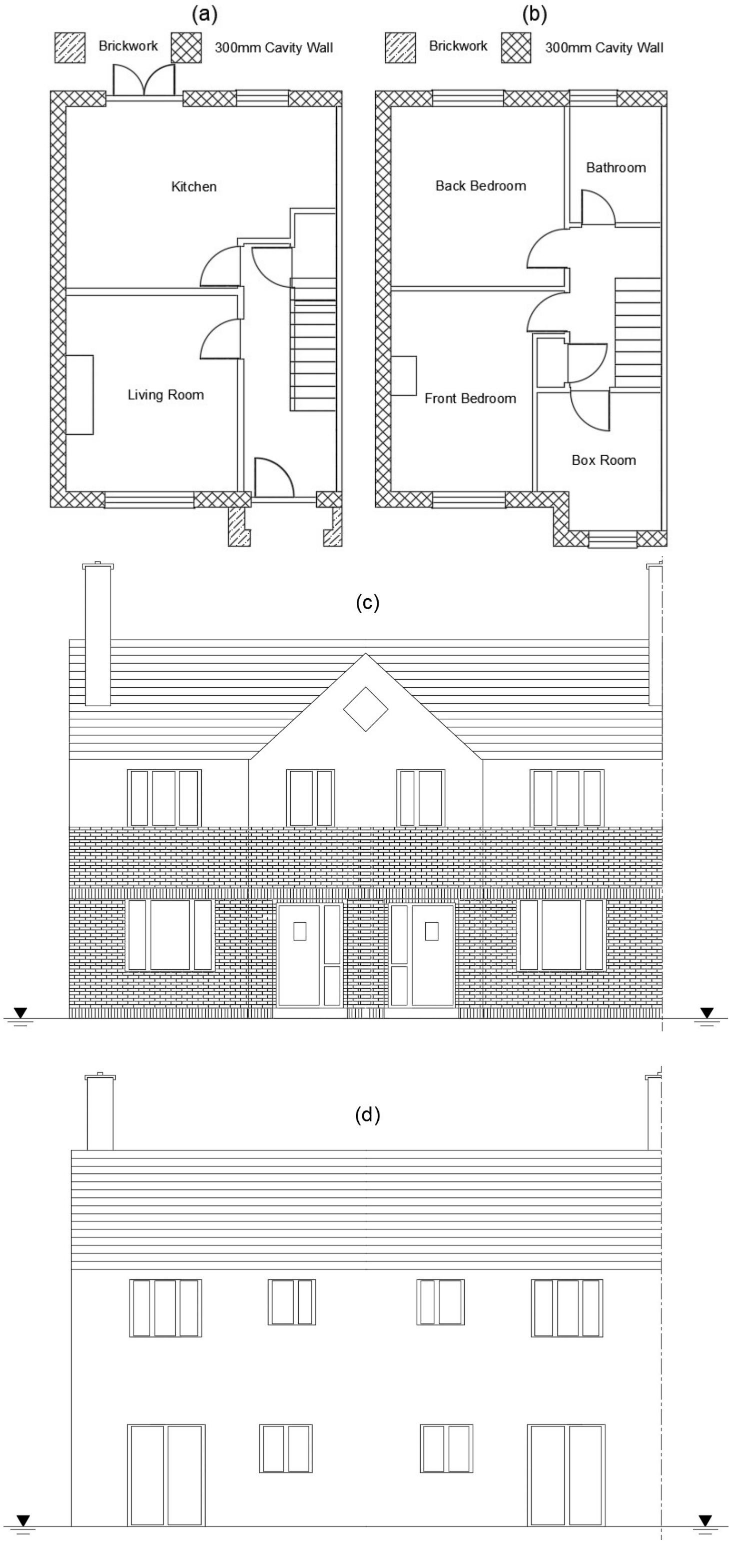


Figure 4.4: (a) Ground floor layout, (b) First floor layout, (c) Front façade and (d) Back façade of the 2000 mid- and end-terrace case study building.

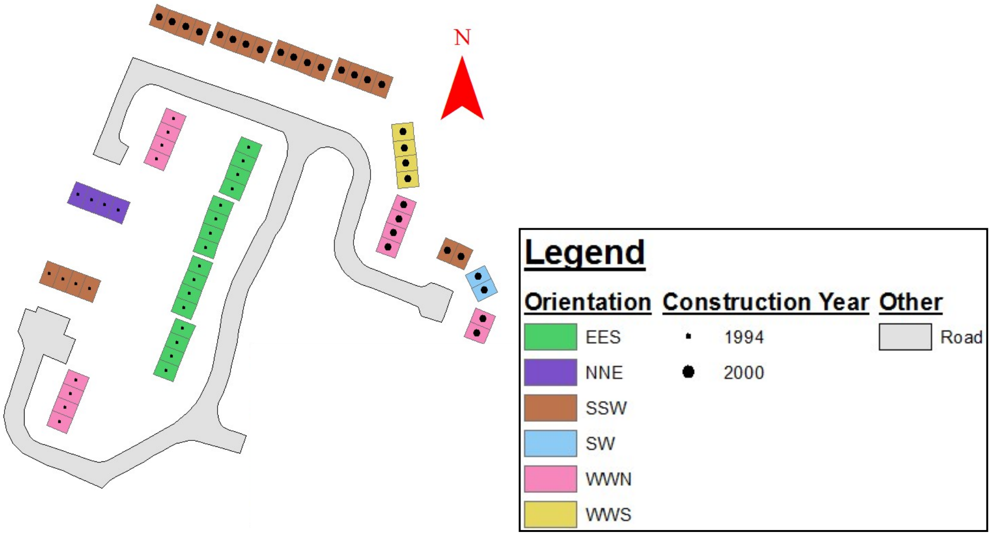


Figure 4.5: Layout of housing in housing estate.

Upon learning of the planned refurbishment works, Co-operative Housing Ireland was contacted for permission to ask residents to participate in the study. In addition, ethical approval from the National University of Ireland, Galway for the study was obtained. Initial contact was made through door-to-door visits, information letters and phone calls to 62 residences. This resulted in 23 of the 62 households becoming involved in the study. The houses received a package of energy efficiency retrofit measures similar to those applied to Retrofit Package A-4(a) in Section 4.3.1.

4.3.2.1 Energy Efficiency Retrofit Measures

In the houses constructed in 1994, the external walls of the buildings are mainly solid walls constructed using cavity concrete masonry blocks with interior timber battens, PIR insulation in-between the timber battens and dry-lining plasterboard (U-value: 0.59 W/m^{2}K). A section of the exterior wall on the ground floor adjacent to the living room is constructed with cavity wall construction with brickwork acting as the external layer. This cavity was empty (U-value: 1.62 W/m^{2}K) pre-retrofit and was pumped with polystyrene bead cavity fill insulation (U-value: 0.32 W/m^{2}K) during the retrofit works (Figure 4.6(b)).

The exterior walls of the houses constructed in 2000 are built using concrete masonry cavity wall construction with an exterior façade of either red brick or concrete blockwork, plaster and paint. The cavity of these houses was originally partially filled with expanded polystyrene board insulation (U-value: 0.46 W/m^{2}K) pre-retrofit. The air gap of the cavity wall was pumped with polystyrene bead cavity fill insulation (U-value: 0.33 W/m^{2}K) (Figure 4.6(c)-(d)).

Figure 4.6: (a) Exterior of ground floor of the 1994 house type, (b) Polystyrene bead insulation and (c)-(d) Installation of polystyrene bead insulation into external walls of the 2000 house type.

The 1994 and 2000 houses had fibreglass insulation (U-value: 0.39 W/m^{2}K) installed between the joists of the attic during the original construction (before the energy efficiency retrofit works) (Figure 4.7(a)). During the retrofit, 300mm of mineral wool insulation (U-value: 0.11 W/m^{2}K) was installed on top of the joists in each house to improve the thermal efficiency of the roof (Figure 4.7(b)). The original windows of the 1994 houses were PVC framed (U-value: 3.1 W/m^{2}K) and the windows of the 2000 houses wooden framed pre-retrofit (U-value: 3.1 W/m^{2}K). The original doors of both houses were wooden framed (U-value: 3.0 W/m^{2}K) pre-retrofit. The windows and doors of the 1994 and 2000 houses were replaced with uPVC windows (U-value: 1.5 W/m^{2}K) and doors (U-value: 1.5 W/m^{2}K) (Figure 4.7(d) and (f)).

The main space heating systems in all the Dublin residences comprised of a gas boiler feeding a central heating system with radiators in each of the rooms of the house. The main domestic hot water (DHW) heating system for the houses was also the gas boiler in combination with a DHW storage tank. The original boiler installed in the 1994 house had an efficiency of 78%. The original boiler in the 2000 house had an efficiency of 77%. The original gas boiler in seven of the 23 houses was replaced at some point before the retrofit works with a more efficient gas boiler (efficiencies varying from 88.4% to 90.9%).

Figure 4.7: (a) Pre-retrofit insulation between timber joists in attic, (b) Post-retrofit insulation on joists in attic, (c) Pre-retrofit windows and doors of 1994 house types, (d) Post-retrofit windows and doors of 1994 house types, (e) Pre-retrofit windows and doors of 2000 house types, (f) Pre-retrofit windows and doors of 2000 house types.

The main space and water heating system in each house was replaced with a high energy efficiency gas boiler and hot water tank. Following the retrofit works, all houses had a gas boiler with an efficiency of 92% (Figure 4.8). A heating system controller allowing the householders to program space and domestic water heating schedules was installed in the entrance hall. In addition, the heating system controller allowed the householder to set a temperature set point to control the room temperature of the ground floor. The upstairs room temperatures were controlled using thermostatic radiator valves (TRVs) installed on each of the radiators. The new heating system controls replaced the old heating system controls, which only allowed for a heating schedule to be set up for when the boiler was in operation. The householders had to manually choose on the old gas boiler whether the boiler had to heat the rooms of the house, the domestic water or simultaneously heat both. With the new heating system controls, the householders can set up separate schedules for the space and water heating. However, householders cannot operate the space and DHW heating simultaneously. If both are selected to operate simultaneously, the DHW takes precedence over the space heating. This constraint meant the householders had to adapt their approach to their space and DHW heating. The new hot water tank has a controller at the base of the water tank allowing the householders to set the maximum temperature the hot water is heated to. This control option was also available on the old hot water storage tanks.

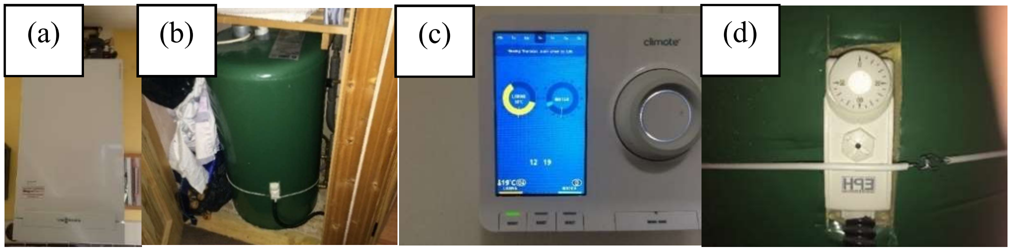


Figure 4.8: Components of the new heating system including (a) Gas boiler, (b) Hot water tank, (c) Heating system controller and (d) Hot water tank thermostat.

A solid fuel open fire, multi-fuel stove, gas fire or electric fire act as a secondary heating system in the living room, but were rarely used. An electric immersion in the hot water tank acts as a secondary heating system. The houses are primarily naturally ventilated using wall vents in the 1994-built houses and trickle window vents in the 2000-built houses. Both ventilation methods worked together in tandem with purge ventilation via the opening and closing of windows and doors, while a mechanical extract fan is used in bathrooms. An extract fan was installed in the kitchen and bathroom of each house during the retrofit works. Background wall vents were cleaned out and serviced in the 1994 house types as part of the retrofit works, while background wall vents were installed in habitable rooms in the 2000 house types.

Finally, each house was given a set of eight energy efficient lightbulbs to install in their homes.

A description of the pre- and post-retrofit building elements, the building elements respective U-values and heating systems is given in Table 4.10. The building element U-values were calculated based on ISO 6946:2007 [312]. The pre-retrofit layers of the building elements were identified in a pre-retrofit survey. Product data sheets and pricing information on the retrofit measures were sourced from the architectural firm overseeing the project [313] The thermal properties of the layers for the building elements were sourced from product information data sheets and the Irish energy performance building regulations [24].

4.3.2.2 Data Collection and Processing

There were three main forms of data collection during the pre-retrofit and post-retrofit monitoring phases: (i) pre-retrofit and post-retrofit participant surveys which form the results of **Chapter 5**, (ii) installation of temperature, relative humidity and electricity consumption data-logging instrumentation and (iii) monthly readings of electricity and gas meters. At least four temperature and relative humidity data loggers were installed in each of the houses.

Six months of pre-retrofit data is available and 15 months post-retrofit. The six pre-retrofit months of data comprises of four heating season months (Feb-May) and two non-heating season months (June-July). DEAP and BER results are based on the energy demand for heating season months in Ireland (October-May). The four months of available pre-retrofit gas consumption data was used together with DEAP to determine an eight-month pre-retrofit gas usage amount for each of the houses. This was done to estimate annual heating savings from the energy efficiency retrofit.

DEAP surveys were carried out for each house pre- and post-retrofit. The U-values for the building elements as shown in Table 4.10 were used together with on-site measured building dimensions. Air-tightness testing was carried out on one of the residential buildings in the housing estate pre-retrofit and 11 of the houses post-retrofit. The air-tightness test results were used in the DEAP surveys. For the houses with no air-tightness testing, default air-tightness values calculated by the DEAP

Table 4.10: Detailed description of the retrofit solutions for the 1994 and 2000 case study buildings and their respective U-values (W/m^{2}K).

Description	Building Element Design	U-Value
Roof Insulation		
Existing: 100mm fibreglass insulation in between joists of roof	1994, 2000	0.39
Retrofit Measures:		
300mm rockwool mineral insulation (λ=0.035W/mK) applied above existing 100mm fibreglass insulation between joists of roof	1994, 2000	0.11
Window and Door Replacement		
Existing: Double glazed PVC windows and PVC doors	1994	3.1/3.0
Existing: Double glazed timber windows and timber doors	2000	3.1/3.0
Retrofit Measures:		
Double glazed uPVC windows & uPVC doors	1994, 2000	1.5
Wall Insulation		
Existing: 215mm hollow block wall with 35mm interior timber battens, insulation between timber battens and 12.5mm plasterboard/ empty cavity wall in section of the exterior wall on the ground floor adjacent to the living room	1994	0.59/1.62
Existing: 300mm cavity block wall with 60mm cavity rigid board insulation, and 35mm air gap	2000	0.46
Retrofit Measures:		
Full fill polystyrene bead cavity fill insulation (λ=0.035W/mK) to section of the exterior wall on the ground floor adjacent to the living room	1994	0.59/0.32
40mm polystyrene bead cavity fill insulation (λ=0.035W/mK) to all external wall	2000	0.33
Heating System		
Existing: Gas boiler with an efficiency of 78%. Various secondary heating systems including open fires, gas fires and electric fires. Natural ventilation used throughout. Original gas boiler with an efficiency of 78% replaced at some point with gas boilers with efficiencies ranging from of 90.3% to 90.9%	1994	
Existing: Gas boiler with an efficiency of 77%. Various secondary heating systems including open fires, solid fuel stoves, gas fires and electric fires. Natural ventilation used throughout. Original gas boiler with an efficiency of 77% replaced at some point with gas boilers with efficiencies ranging from of 88.4% to 90.9%	2000	
Retrofit Measures:		
Main Space and Water Heating – Gas boiler with efficiency of 92% and hot water tank. Existing secondary heating system left as is. Extract fan installed in kitchen and bathroom. Background wall vents cleaned out and serviced	1994	
Main Space and Water Heating – Gas boiler with efficiency of 92% and hot water tank. Existing secondary heating system left as is. Extract fan installed in kitchen and bathroom. Background wall vents installed in habitable rooms	2000	

software were used instead. The calculated average external temperature and solar intensity falling on the façade of a building was input into DEAP to calculate the theoretical gas demand for comparison to the actual energy consumption. The average external temperature and solar intensity falling on the façade of a building was calculated using weather data collected from Dublin airport [314]. Dublin airport is located within an 11 km radius of the housing estate location.

The theoretical gas energy demand for February to May was compared to the actual gas energy consumption to determine the energy performance gap (EPG). The actual gas consumption for the remaining days of the heating season pre-retrofit was estimated for each building, assuming the EPG calculated for four of the eight heating months remained constant for the eight months. To be consistent, the same process was applied to each building for the post-retrofit data. Pre-retrofit data is based on gas meter data collected from the 13th February 2015 to the 29th May 2015. Post-retrofit data is based on gas meter data collected from the 13th February 2016 to the 27th May 2016. Gas meter readings were recorded once a month for each of the houses.

Both the pre-retrofit and post-retrofit theoretical and actual gas consumptions are then normalised using the Heating Degree Days (HDDs) experienced at Dublin Airport. A base temperature of 15.5°C is assumed by SEAI in their Irish energy consumption analysis [43] and a base temperature of 15.5°C was used when calculating the HDDs experienced at Dublin Airport in this analysis. The normalised gas usage data (kWh/HDD) for each phase was multiplied by the average HDDs experienced at Dublin Airport for the Irish heating season for 10 years starting from 2005.

Electricity was not included in the analysis as DEAP does not account for the electricity demand of appliances. As such, a direct comparison between estimated electricity demand and actual electricity consumption would be inaccurate, as highlighted by results in Table 2.5.

Four or five rooms had temperature and relative humidity data loggers installed. Lascar EL-USB-2+ acted as the temperature and relative humidity data loggers. The data loggers have an accuracy of ±0.45°C for temperature and ±2.05% for relative humidity. Refer to Appendix D for further details on the data loggers. These data loggers were unobtrusive and recorded data at one-hour intervals pre-retrofit and 15-minute intervals post retrofit. The internal environment data loggers were installed at heights ranging from 0.5m to 2m. The height installation depended on the both the available surfaces in a house and the householders. In some instances, householders did not want the data loggers to be installed on walls in case the paint on the wall or wallpaper was damaged when removing the data logger. For other houses, data loggers had to be installed at heights to avoid children moving the data loggers. Despite a researcher installing the data loggers, internal environment data for individual rooms for a number of houses were missing for data analysis. The amount of missing data varied from case to case. Reasons for the missing data included (i) loss of the data logging instrumentation by the householder, (ii) loss of battery power in the data logging instrumentation, (iii) full capacity of the data logger's internal memory, (iv) malfunction of data logging instrumentation, (v) data loggers moved by a householder and (vi) data loggers in direct sunlight.

All the temperature data collected from the data loggers for each room were plotted for visual inspection to identify any errors or anomalies. Reasons identified for exclusion of data included (i) data logger moved near heat source or window and (ii) temperature profile of room significantly different to other rooms of house with no logical explanation.

4.4 Results

4.4.1 Theoretical Case Study Buildings

4.4.1.1 Cost-Optimal

Figure 4.9 shows the cost-optimal results of the theoretical case study building without any retrofit measures (0) and the applied retrofit packages (1-5(b)) from a householder perspective. The operational cost savings achieved from the energy efficiency retrofit measures did not outweigh the initial investment costs for most of the retrofit packages for the semi-detached house. Apart from applying mineral wool or rock wool insulation to the joists of the attic, all other retrofit packages were found to have larger LCCs than the original building.

Current SEAI grants available to householders, given in Table 4.1, were accounted for in the results of Figure 4.9(b). Due to the grants, the LCC gap between the existing original case study building and the retrofit packages reduced. However, only two

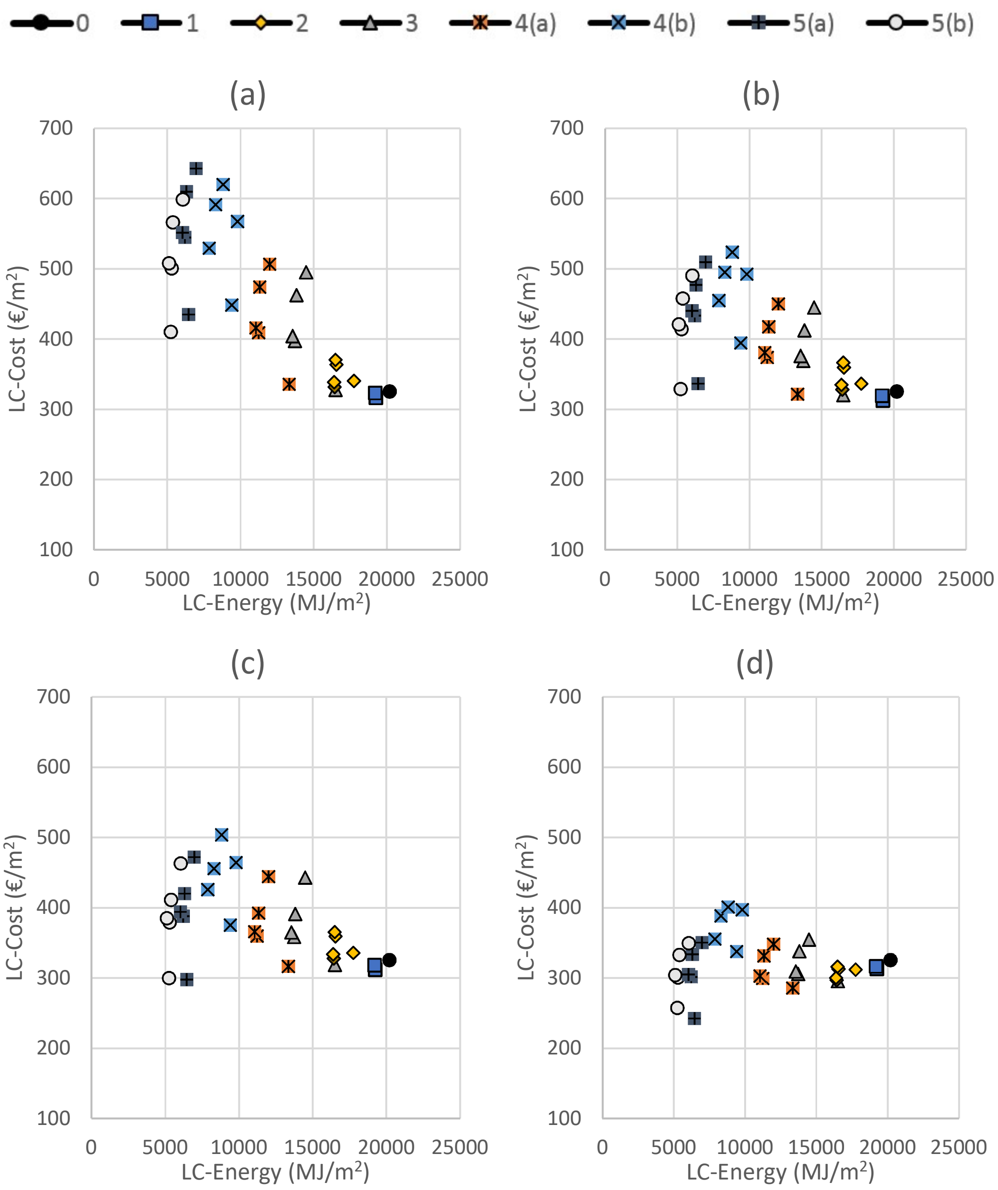


Figure 4.9: Cost-optimal results of the theoretical case study building and the applied retrofit packages from a householder perspective (a) excluding grants available, (b) including grants available to householders to retrofit home, (c) excluding VAT for materials and labour and including grants available to householders to retrofit home and (d) assuming a grant covering 50% of the costs is available.

additional retrofit packages (Retrofit Package A-S3 and A-S4(a)) result in lower LCC compared to the original building without any retrofit measures.

VAT for construction materials and labour is currently at 13.5%. When both grants available were included and the VAT for materials and labour excluded, two additional retrofit packages (Retrofit Package A-S5(a)/(b)) reduce the LCC of the existing building (Figure 4.9(c)). The two additional retrofit packages were deep retrofits with basic thermal fabric measures and advanced heating system measures.

For houses involved in the SEAI Better Energy Communities Scheme, grants covering up to 80% of the energy efficiency retrofit costs are available (Table 4.2). Assuming there was a grant available covering 50% of the retrofit costs, 22 of the 35 retrofit packages reduced the LCC of the building (Figure 4.9(d)). A 50% grant is available to housing association homes and private households in fuel poor homes. However, private households in non-fuel poor homes and local authority homes can avail of a 50% grant if they undergo a deep retrofit and achieve a BER of A3. Retrofit Package A-S5(a) had the lowest LCC of the 35 retrofit packages. 10 of the 35 retrofit packages analysed achieved an A2 BER (A-E S5(a)/S5(b)). The 10 retrofit packages include advanced heating system measures in addition to either basic or advanced thermal fabric measures. Six of these 10 retrofit packages lowered the LCC of the existing building when 50% of the costs were assumed to be covered through a grant. The four retrofit packages designed to achieve an A2 BER that did not lower the LCC of the existing building when 50% of the costs were assumed to be covered through a grant were based on using external insulation. Furthermore, the internal insulation-based packages that achieved an A2 BER while lowering the LCC of the original semi-detached building did not account for the cost of removing and reinstalling kitchen cabinets etc. to add the internal insulation to the walls.

Figure 4.10(a) shows the cost-optimal results of the theoretical building and the applied retrofit packages from a societal perspective. Five shallow retrofit packages which installed mineral wool and rock wool insulation on the joists of the attic reduced the LCC of the theoretical case study building. Once the grants available to householders were considered (Figure 4.10(b)), eight of the 35 retrofit packages had lower LCC compared to the existing theoretical building. 22 of the retrofit packages reduced the LCC of the existing building when assuming 50% of the costs are covered by a grant (Figure 4.10(c)). In both Figure 4.10(b) and Figure 4.10(c), Retrofit Package A-S5(a) had the lowest LCC from a societal perspective.

4.4.1.2 Life Cycle Cost and Life Cycle Environmental

Figure 4.11 shows the LCC and life cycle environmental impact for the various steps of Retrofit Package A. The LCC results shown in Figure 4.11 do not account for any

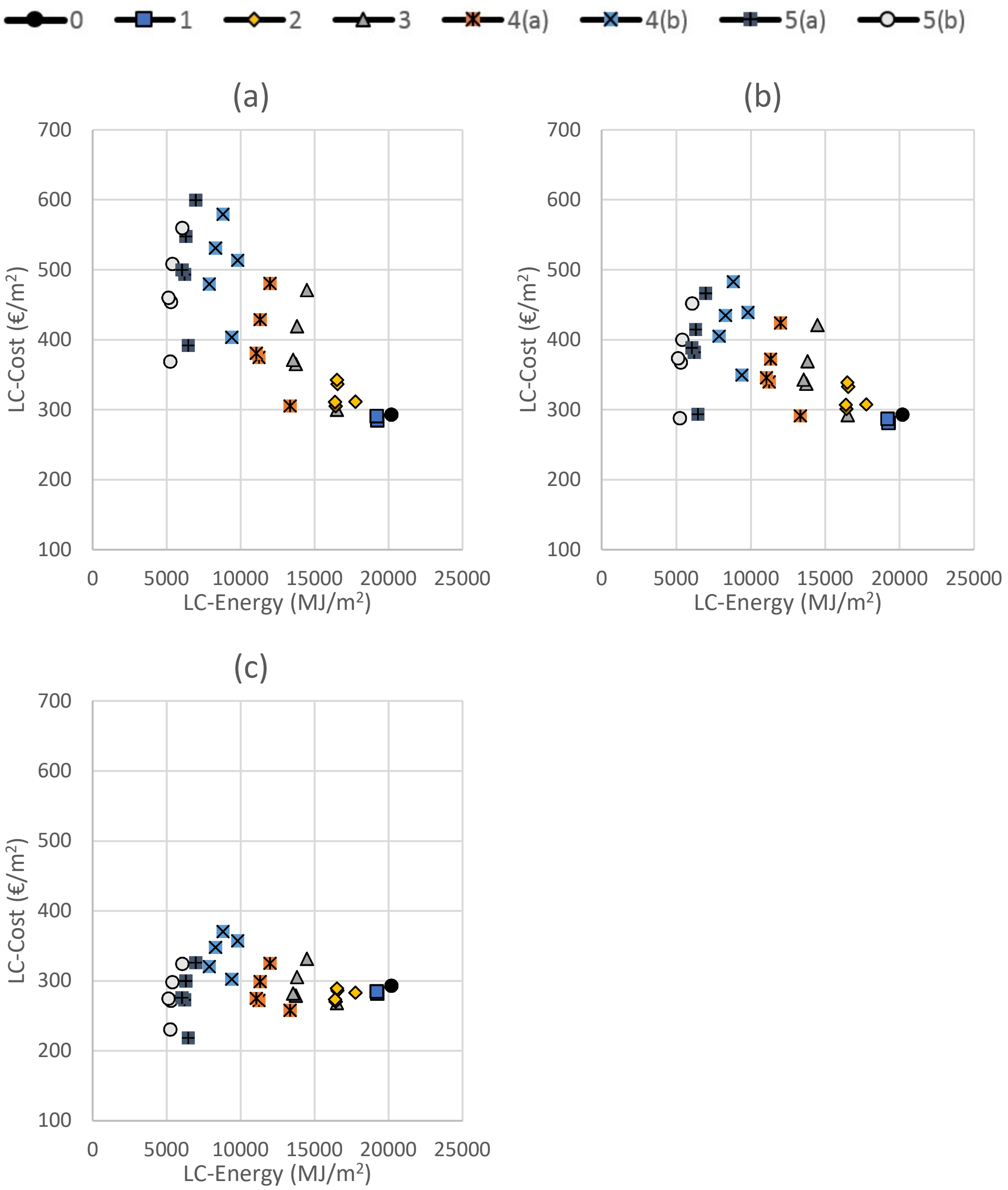


Figure 4.10: Cost-optimal results of the theoretical case study building and the applied retrofit packages from a societal perspective (a) excluding grants available (b) including grants available to householders to retrofit home and (c) assuming a grant covering 50% of the costs.

grant available or VAT tax break. The original theoretical building reduced its life cycle energy and life cycle GWP following each retrofit step. However, the LCC and other LC environmental indicators did not follow this trend as the buildings become more energy efficient. The same was found for the Retrofit Packages B, C, D and E.

Switching from a gas fuel heating system to an electric heating system (S4(a) to S4(b)) significantly reduced the life cycle energy and life cycle GWP. However, the embodied impact of the ASHP heating system and the environmental impact of the Irish electricity grid resulted in increases in the life cycle ODP, life cycle AP, life cycle EP and life cycle POCP. Moving to the nZEB new build standards for the gas fuelled buildings was achieved using ETSC and MCPV. Despite the operational ODP savings from the renewable technology, the initial environmental investment in producing the renewable technology increased the LC impact of ODP when moving from retrofit steps S4(a) to S5(a).

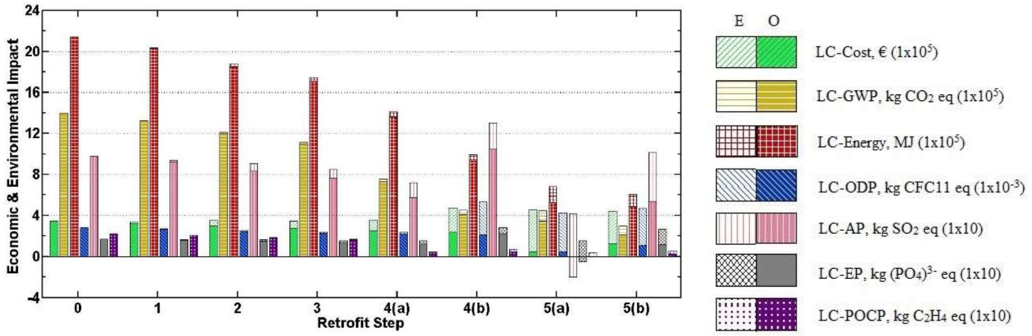


Figure 4.11: LCC and life cycle environmental impact for the various steps of Retrofit Package A.

Environmentally friendly materials come at an additional cost. For insulation on the joists of the roof, mineral wool insulation was used as a retrofit measure in retrofit packages A-C and rock wool insulation was used as a retrofit measure in retrofit packages D-E, respectively. While rock wool was more environmentally friendly in each of the assessed environmental indicators, mineral wool was financially the less expensive option. For example, rock wool had an embodied impact 28% and 38% that of mineral wool in terms of energy and GWP. However, mineral wool is €10/m^2 (i.e. 51%) less expensive.

EPS external insulation, used in retrofit package B, was less expensive than wood fibre external insulation in terms of economic cost, which was used in retrofit package D. From an environmental standpoint, EPS is also the better option than wood fibre in terms of its embodied energy, AP and EP impact. However, wood fibre board has less of a GWP, ODP and POCP environmental impact. Aluclad triple glazed windows (employed in retrofit packages C and E) are a more expensive option compared to uPVC triple glazed windows (employed in retrofit package B and D), but are more environmentally friendly in terms of GWP and POCP.

As the buildings became more energy efficient, the embodied impact of the retrofit measures became the main contributor to the LCC, life cycle ODP, life cycle AP, life cycle EP and life cycle POCP (Table 4.11). In some cases, the embodied impact of the materials represented the whole life cycle indicator impact. The LCC results shown in Table 4.11 do not account for any grant available or VAT tax break.

Table 4.11: Maximum embodied share of a building's life cycle for each of the economic and environmental indicators.

Case Study/Indicator	Cost (%)	GWP (%)	EN (%)	ODP (%)	AP (%)	EP (%)	POCP (%)
A	89	32	23	89	100	100	100
B	91	36	28	87	100	100	95
C	89	32	26	87	100	100	91
D	91	26	36	86	100	100	90
E	90	30	24	87	100	100	90

Table 4.12 shows the retrofit package with the minimum and maximum LC impact for each of the economic and environmental indicators. As can be seen from the results in Table 4.12, no one retrofit package is the optimum solution for every indicator evaluated. The LCC results shown in Table 4.12 do not account for any grant available or VAT tax break.

Table 4.12: Retrofit package with the minimum and maximum LC impact for each of the economic and environmental indicators.

	Cost *€*	GWP *kgCO_2eq*	EN *MJ*	ODP *kg CFC11 eq*	AP *kg SO_2 eq*	EP *kg $(PO_4)^{3-}$ eq*	POCP *kg C_2H_4 eq*
Min	A-C S1	D S5(b)	E S5(b)	D S4(a)	A S5(a)	B S3	A S5(a)
Max	D S5(a)	S0	S0	C S4(b)	C S4(b)	C S4(b)	S0

4.4.1.3 Sustainable Index Factor (SIF)

The SIF was used to assess the optimum retrofit package for the theoretical case study building both from a householder's perspective and societal perspective based on the weightings discussed in Section 4.2.6. Shown in Table 4.13 are the impacts of the retrofit packages from a householder's perspective considering LCC and life cycle energy. For the theoretical analysis, all the buildings were assumed to continuously have an average temperature and relative humidity within the thermal comfort range as defined by EN15251 [303] for the social indicator. This was due to the limitations of DEAP, which is a quasi-steady state model that only estimates the average monthly indoor temperature. It cannot assess the hourly temperature profile of a building.

Table 4.14 shows the impacts of the retrofit packages from a householder's perspective but including available grants. The SIF results of Table 4.15 account for available grants and exclude VAT for materials and labour and Table 4.16 assumes that 50% of the retrofit cost is covered through a grant.

Table 4.13: SIF impacts of the retrofit packages from a householder's perspective.

Retrofit step/ package	S0	S1	S2	S3	S4(a)	S4(b)	S5(a)	S5(b)
A	1.107	1.075	1.055	1.013	0.937	0.922	0.835	0.785
B	1.107	1.075	1.014	1.047	0.991	1.004	0.966	0.909
C	1.107	1.075	1.042	0.995	0.939	1.024	0.914	0.856
D	1.107	1.079	1.018	1.090	1.034	1.039	1.009	0.951
E	1.107	1.079	1.046	0.995	0.940	0.945	0.914	0.857

Table 4.14: SIF impacts of the retrofit packages from a householder's perspective accounting for available grants.

Retrofit step/ package	S0	S1	S2	S3	S4(a)	S4(b)	S5(a)	S5(b)
A	1.137	1.101	1.083	1.037	0.956	0.917	0.791	0.753
B	1.137	1.101	1.042	1.046	0.986	0.975	0.908	0.867
C	1.137	1.101	1.072	1.007	0.947	1.012	0.868	0.827
D	1.137	1.106	1.046	1.092	1.032	1.013	0.953	0.913
E	1.137	1.106	1.076	1.008	0.948	0.929	0.869	0.829

Table 4.15: SIF impacts of the retrofit packages from a householder's perspective accounting for available grants and excluding VAT for materials and labour.

Retrofit step/ package	S0	S1	S2	S3	S4(a)	S4(b)	S5(a)	S5(b)
A	1.149	1.112	1.095	1.047	0.963	0.915	0.768	0.739
B	1.149	1.112	1.054	1.043	0.980	0.959	0.875	0.843
C	1.149	1.112	1.085	1.012	0.948	1.005	0.843	0.812
D	1.149	1.117	1.058	1.107	1.044	1.015	0.939	0.907
E	1.149	1.117	1.089	1.013	0.949	0.920	0.844	0.812

Implementing the basic thermal fabric retrofit measures for all the building elements and introducing a gas boiler or heat pump with renewable energy technology were found to be the optimum packages of energy efficiency measures in Table 4.13 to Table 4.16. The ASHP retrofit packages (S4(b) and S5(b)) outperformed most of their gas boiler retrofit package counterpart (S4(a) and S5(a)) apart from package C and when a grant of 50% is available. Regardless of the retrofit package implemented on the case study building, all outperformed the existing building.

Table 4.16: SIF impacts of the retrofit packages from a householder's perspective assuming a grant of 50% is available.

Retrofit step/ package	S0	S1	S2	S3	S4(a)	S4(b)	S5(a)	S5(b)
A	1.203	1.164	1.124	1.074	0.980	0.925	0.737	0.727
B	1.203	1.164	1.074	1.039	0.966	0.941	0.821	0.802
C	1.203	1.164	1.094	1.008	0.935	0.995	0.791	0.771
D	1.203	1.166	1.076	1.084	1.011	0.977	0.866	0.847
E	1.203	1.166	1.096	1.007	0.934	0.900	0.789	0.770

Table 4.17 shows the impacts of the retrofit packages from a societal perspective including all indicators. Unlike the results of Table 4.13 to Table 4.16, many of the retrofit packages involving switching to an electric ASHP were found to be worse than the existing building. Four of the top five retrofit packages included replacing the existing gas boiler with a more efficient gas boiler. Unlike Table 4.13 to Table 4.15, the gas boiler retrofit packages (S4(a)) outperformed their ASHP retrofit package counterpart (S4(b)). This trend continues once grants are accounted for in the analysis (Table 4.18 and Table 4.19).

Table 4.17: SIF impacts of the retrofit packages from a societal perspective.

Retrofit step/ package	S0	S1	S2	S3	S4(a)	S4(b)	S5(a)	S5(b)
A	1.044	1.014	1.006	0.966	0.869	0.993	0.870	0.885
B	1.044	1.014	0.967	1.016	0.957	1.092	1.032	1.019
C	1.044	1.015	1.002	0.965	0.905	1.115	0.980	0.967
D	1.044	1.018	0.970	1.049	0.989	1.117	1.064	1.051
E	1.044	1.018	1.005	0.965	0.905	1.033	0.979	0.967

Table 4.18: SIF impacts of the retrofit packages from a societal perspective accounting for grants available.

Retrofit step/ package	S0	S1	S2	S3	S4(a)	S4(b)	S5(a)	S5(b)
A	1.077	1.043	1.037	0.992	0.890	0.987	0.820	0.849
B	1.077	1.043	0.998	1.016	0.951	1.060	0.966	0.972
C	1.077	1.043	1.036	0.979	0.914	1.101	0.929	0.935
D	1.077	1.047	1.001	1.054	0.988	1.090	1.004	1.010
E	1.077	1.047	1.040	0.979	0.914	1.016	0.929	0.935

Table 4.19: SIF impacts of the retrofit packages from a societal perspective assuming 50% of the costs are covered by a grant.

Retrofit step/ package	S0	S1	S2	S3	S4(a)	S4(b)	S5(a)	S5(b)
A	1.132	1.096	1.066	1.019	0.906	0.998	0.789	0.837
B	1.132	1.096	1.018	1.012	0.937	1.041	0.912	0.931
C	1.132	1.097	1.045	0.975	0.900	1.090	0.875	0.894
D	1.132	1.098	1.020	1.030	0.954	1.051	0.930	0.949
E	1.132	1.098	1.046	0.973	0.898	0.994	0.873	0.892

With grants, more of the retrofit packages including renewable technology became more viable options. Assuming a grant covering up to 50% of the costs, Retrofit Package A-5(a) was the best option both from a householder's perspective and societal perspective.

4.4.2 Monitored Case Study Buildings

4.4.2.1 Cost-Optimal

While building energy efficiency retrofits can be effective in theory, how the people use energy both before and after a retrofit plays a significant role in the energy savings achieved. Shown in Figure 4.12(a) is the LCC and life cycle energy of the monitored houses in Dublin based on the theoretical gas demand determined using DEAP, while Figure 4.12(b) shows the LCC and life cycle energy of the monitored Dublin houses based on actual gas consumption.

As can be seen in Figure 4.12(b), the actual gas consumption varied significantly compared to the theoretical gas demand. Based on the measured gas consumption and assuming it remained constant over 30 years, the estimated actual energy consumption over 30 years ranged from 3599 MJ/m^2 to 17218 MJ/m^2. The theoretical gas demand range in contrast was much narrower, ranging from 7467 MJ/m^2 to 14738 MJ/m^2. The theoretical LCCs did not reduce for any house studied over 30 years after being retrofitted. The theoretical payback periods ranged from 31 to 71 years. The large payback periods were due to the installation of new windows as part of the retrofit. Based solely on economic payback related to energy savings, window retrofits are also not recommended in terms of cost payback for houses constructed from the 1980's onwards in Ireland [20].

However, due to the poor performance of the existing windows in allowing drafts to enter the house, they had to be replaced as part of the energy efficiency improvements. The window and door pricing obtained from the architect overseeing the retrofit works was compared to the window pricing received from a window supplier for the theoretical case study analysed in Section 4.4.1. The pricing information from the architect was €1019 to €1687 more than the pricing based on the information received from the window supplier. If the window supplier information was used instead of the architect pricing information, only one of the monitored houses theoretical LCCs would reduce over 30 years after being retrofitted. The theoretical payback periods would change from a range of 31 to 71 years to a range of 27 to 56 years. For the remainder of the analysis however, the architect pricing information is used.

Based on measured gas consumption, only one house would reduce its LCC over 30 years after being retrofitted, assuming that their gas consumption remains constant over 30 years. Six of the households increased their gas consumption and would not payback the investment costs assuming that their gas consumption remains constant over 30 years. Households who saved energy have payback periods ranging from 23 to 642 years.

Homes that are owned by housing associations, and which are retrofitted as part of the SEAI Better Energy Communities grant programme, can have up to 50% of the costs of the energy efficiency retrofit works funded [301]. Assuming the works on the Dublin housing received 50% of the funding, 19 of the 21 houses would theoretically reduce their LCC over 30 years (Figure 4.12(c)). The payback periods would range from 15 to 36 years. For all the houses to theoretically payback the cost of the retrofit works in 30 years, 58% of the costs would have to receive external funding.

However, based on the actual gas consumption measured, only six houses would reduce their LCCs over 30 years, assuming that their gas consumption remained constant over 30 years (Figure 4.12(d)). For the households which saved energy, their payback periods would range from 12 to 321 years.

In reality, the energy efficiency retrofit works of the monitored case study buildings were funded by a combination of the SEAI Better Energy Communities grant programme and a rent increase for the householders. The grant from SEAI was to cover 95% of the retrofit works. However, the discounted present value rent increase

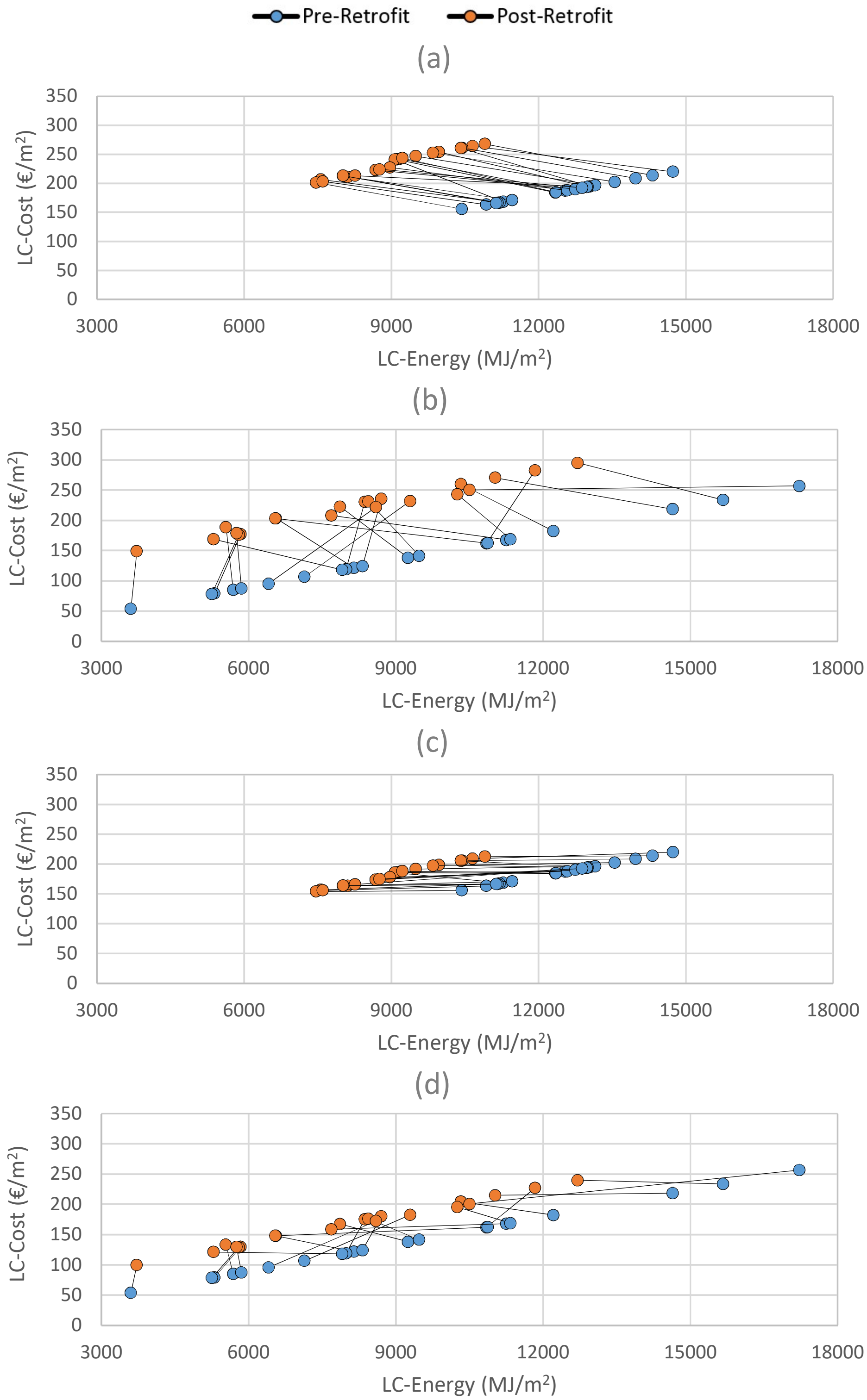


Figure 4.12: LCC and life cycle energy of the monitored Dublin houses based on (a) theoretical gas demand, (b) actual gas demand, (c) theoretical gas demand and accounting for grants available and (d) actual gas demand and accounting for grants available.

experienced by the householders was between 8-16% of the retrofit cost. This difference may have been caused by the architect not including overheads in the pricing information given to the researchers or the property managers of the housing units increasing the rent higher than was required. The reason for this difference, however, was not able to be confirmed.

For the householders living in the houses constructed in 1994, they experienced a weekly rent increase of €3 for five years. For the householders living in the 1994 houses, the payback periods for their investment in the retrofit works would be paid back theoretically in three to six years after discounting the rent to present value (Figure 4.13(a)). Only three of the 11 households living in the houses constructed in 1994 would actually see a return on their investment within seven years based on their actual consumption (Figure 4.13(b)). Three of the 11 households living in the houses constructed in 1994 increased their energy consumption with the remaining five household pay back periods ranging from seven to 31 years.

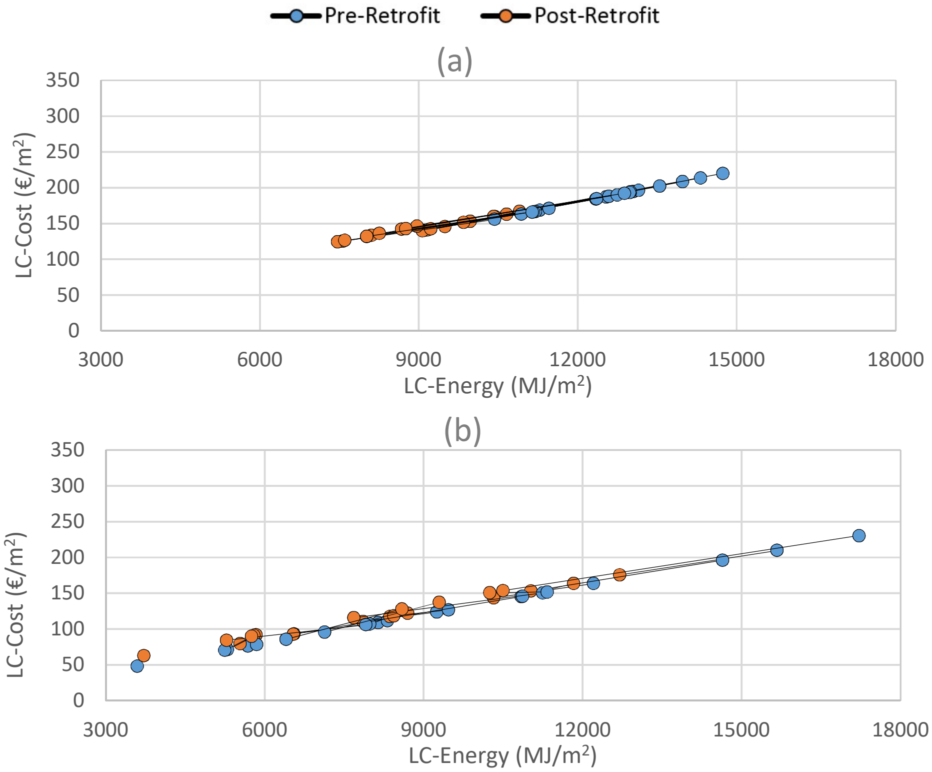


Figure 4.13: LCC and life cycle energy of the monitored Dublin houses based on (a) the rent increase and theoretical gas demand and (b) the rent increase and actual gas demand.

For the householders living in the houses constructed in 2000, they experienced a weekly rent increase of €6 for five years which should be paid back to the householders theoretically within a five to eight-year period (Figure 4.13(a)). Only two of the houses will be paid back within 10 years assuming their gas consumption remains constant. (Figure 4.13(b)). Four of the 10 households living in the houses constructed in 2000 increased their energy consumption with the remaining four household pay back periods ranging from nine to 108 years. Overall, 11 of the households will have paid back their rent increase within 30 years.

4.4.2.2 LCC and Life Cycle Environmental

The range of the embodied share of the building's life cycle assessment measures following the energy efficiency retrofit for each of the economic and environmental indicators based on the theoretical and actual gas usage of the monitored houses is given in Table 4.20. The range of the embodied share of the building's life cycle assessment measures was wider based on actual gas consumption compared to theoretical demand. Differences in the ranges were as large as 23% and as low as 5% depending on the indicator. For life cycle ODP, life cycle AP, life cycle EP and life cycle POCP, the embodied share of the building's life cycle outweighed the operational share of the building's life cycle. For life cycle GWP and life cycle energy, the embodied share was relatively small compared to the other evaluated indicators.

Table 4.20: Range of the embodied share of the building's life cycle assessment measures following the energy efficiency retrofit for each of the economic and environmental indicators based on the theoretical and actual gas usage.

	Cost (%)	GWP (%)	Energy (%)	ODP (%)	AP (%)	EP (%)	POCP (%)
Theoretical	41-48	3-4	3-5	75-79	56-61	73-78	36-42
Actual	38-66	3-9	3-10	61-84	50-77	69-88	31-61

4.4.2.3 Sustainable Index Factor (SIF)

Houses experienced varying benefits following the energy efficiency retrofit works in terms of energy savings and thermal comfort. Table 4.21 shows the energy savings, average temperature change and the amount of time the average temperature was inside the thermal comfort range for a naturally ventilated residential house as defined by EN 15251 [303] following the energy efficiency retrofit works. Table 4.22 shows the energy savings, average relative humidity change and the amount of time the average relative humidity was inside the thermal comfort range for a naturally ventilated residential house as defined by EN 15251 [303] following the energy efficiency retrofit works.

The case study results of Table 4.21 and Table 4.22 are organised in terms of construction type and lowest to highest pre-retrofit gas consumption. Only three households reduced their gas energy consumption more than estimated by DEAP. The houses with a higher pre-retrofit gas consumption tended to have larger energy savings and the houses with a lower pre-retrofit gas consumption tended to have larger thermal comfort improvements. On average, the houses experienced an energy savings deficit (ESD) of 62% with seven of the households increasing their gas consumption.

All comparable non-erroneous temperature and relative humidity data available for rooms during the heating periods of the pre-retrofit and post-retrofit monitoring phases were used in the analysis. As the temperature data was used to assess whether individual houses experienced a change in temperature and relative humidity rather than comparing the size in temperature and relative humidity changes across multiple households, all comparable temperature and relative humidity data was used. A two-sample z-test for comparing two means was used for examining whether houses experienced a statistically significant change (95% confidence level) in average house temperature and relative humidity profiles.

As can be seen from Table 4.21, nine of the cases experienced energy savings and temperature improvements, whereas seven of the houses experienced improved internal temperatures but no energy savings, and four of the houses saved energy while sacrificing some internal comfort in terms of temperature. As can be seen from Table 4.22, all but two of the houses were always within the relative humidity thermal comfort range pre-retrofit. The household (Case 17) which was outside of the relative humidity thermal comfort range for 5% of the pre-retrofit time had the lowest pre-retrofit internal temperature. Case 17 was within the relative humidity thermal comfort range all the time post-retrofit.

10 days of post-retrofit temperature and relative humidity data is missing in March for Case 20 and is excluded from the results given in Table 4.21 and Table 4.22.

Table 4.21: Energy savings, average temperature changes and the amount of time the average temperature was inside the thermal comfort range following the energy efficiency retrofit works.

Case	House Type	THE-Sav (MJ)	ACT-SAV (MJ)	ESD (%)	Temp Change (°C)	PRE-Inside Limit (%)	POST-Inside Limit (%)	Rooms
1	1994-MT	2386	321	87	0.32	77	85	LR, FBR
2[2]	1994-MT	2474	-29	101	0.94*	97	100	KT, LR, FBR, BBR, Box
3[1]	1994-MT	2664	1141	57	0.80*	95	98	KT, FBR
4[1]	1994-MT	1685	907	46	-1.21*	94	80	KT, LR, FBR, Box
5	1994-ET	2948	1277	57	0.87*	51	72	KT, LR, FBR
6	1994-ET	2509	-28	101	1.80*	72	98	LR, FBR, BBR
7[1]	1994-ET	2251	-426	119	0.98*	99	100	LR, BBR
8	1994-ET	2671	3083	-15	-0.60*	95	92	KT, LR, FBR, BBR
9	1994-ET	1990	1469	26	-0.15	100	100	KT, LR
10	1994-ET	2288	2612	-14	-0.11	100	100	KT, LR, FBR
11	1994-ET	2587	2184	16	0.34	99	99	LR, BBR
12	2000-MT	-	-	-	-	-	-	-
13[1]	2000-MT	2697	-150	106	1.19*	73	93	KT, LR, Box
14	2000-MT	2416	-142	106	1.68*	50	95	LT, BBR, Box
15[1]	2000-MT	2682	2166	19	-0.42*	68	57	KT, Box
16	2000-MT	3696	1038	72	0.83*	90	99	KT, LR, BBR
17	2000-ET	2917	185	94	2.21*	22	72	KT, LR, BBR
18	2000-ET	3258	824	75	-	-	-	N/A
19	2000-ET	2573	347	87	1.70*	64	100	KT, LR
20	2000-ET	2932	2876	2	0.84*	100	N/A	KT, LR, BBR
21	SD-ET	2551	-1326	152	2.31*	40	86	FBR
22	SD-ET	3286	-1301	140	1.67*	59	92	KT, LR, Box
23	SD-ET	3242	5178	-60	1.06*	98	100	KT, LR, BBR

Abbreviations

ACT: Actual
ESD: Energy Saving Deficit
ET: End-Terrace
MT: Mid-Terrace
POST: Post-Retrofit
PRE: Pre-Retrofit
SAV: Savings
SD: Semi-Detached
Temp: Average House Temperature
THE: Theoretical
*-Experience statistically significant change
[1]-Temperature data is from the 25th February 2015
[2]-Temperature data is from the 1st April 2015

However, all other temperature and relative humidity data available post-retrofit is within the thermal comfort range for a naturally ventilated residential house.

The SIF was used to assess the sustainability of the case study houses from a householder's perspective (Table 4.23). As part of the SIF methodology, the life cycle cost, life cycle energy and indoor air quality indicators were normalised based on the

Table 4.22: Energy savings, average relative humidity changes and the amount of time the average relative humidity was inside the thermal comfort range following the energy efficiency retrofit works.

Case	House Type	THE-Sav (MJ)	ACT-SAV (MJ)	ESD (%)	RH Change (%)	PRE-Inside Limit (%)	POST-Inside Limit (%)	Rooms
1	1994-MT	2386	321	87	-0.58	100	100	LR, FBR
2[2]	1994-MT	2474	-29	101	-2.27*	100	100	KT, LR, FBR, BBR, Box
3[1]	1994-MT	2664	1141	57	2.54*	100	100	KT, FBR
4[1]	1994-MT	1685	907	46	2.07*	100	100	KT, LR, FBR, Box
5	1994-ET	2948	1277	57	-0.21	100	100	KT, LR, FBR
6	1994-ET	2509	-28	101	-2.12*	100	100	LR, FBR, BBR
7[1]	1994-ET	2251	-426	119	-0.12	100	100	LR, BBR
8	1994-ET	2671	3083	-15	0.95	100	100	KT, LR, FBR, BBR
9	1994-ET	1990	1469	26	1.42*	100	100	KT, LR
10	1994-ET	2288	2612	-14	5.98*	100	100	KT, LR, FBR
11	1994-ET	2587	2184	16	1.89*	100	100	LR, BBR
12	2000-MT	-	-	-	-	-	-	-
13[1]	2000-MT	2697	-150	106	0.12	100	100	KT, LR, Box
14	2000-MT	2416	-142	106	0.20	100	100	LT, BBR, Box
15[1]	2000-MT	2682	2166	19	1.03	100	100	KT, Box
16	2000-MT	3696	1038	72	3.73*	100	100	KT, LR, BBR
17	2000-ET	2917	185	94	-5.60*	95	100	KT, LR, BBR
18	2000-ET	3258	824	75	-	-	-	N/A
19	2000-ET	2573	347	87	-4.41*	100	100	KT, LR
20	2000-ET	2932	2876	2	1.95*	100	N/A	KT, LR, BBR
21	SD-ET	2551	-1326	152	-2.35*	99	99	FBR
22	SD-ET	3286	-1301	140	-3.65*	100	100	KT, LR, Box
23	SD-ET	3242	5178	-60	2.59*	100	100	KT, LR, BBR

Abbreviations

ACT: Actual	SAV: Savings
ESD: Energy Saving Deficit	SD: Semi-Detached
ET: End-Terrace	THE: Theoretical
MT: Mid-Terrace	*-Experience statistically significant change
POST: Post-Retrofit	[1]-Temperature data is from the 25th February 2015
PRE: Pre-Retrofit	[2]-Temperature data is from the 1st April 2015
RH: Relative Humidity	

average theoretical pre- and post-retrofit life cycle cost, life cycle energy and indoor air quality indicators results of the 20 cases. The theoretical life cycle cost is based on the householders rent increase. For the social indicators theoretical results, all the buildings were assumed to continuously have an average temperature and relative humidity within the thermal comfort range as defined by EN15251 [303] for the social indicator. This was due to the limitations of DEAP, which is a quasi-steady state model that only estimates the average monthly indoor temperature. It cannot assess the hourly temperature profile of a building.

For the SIF impact results given in Table 4.23, if a case has a score of one, the results are representative of the overall sustainability impact of the average theoretical pre- and post-retrofit results of the 20 cases. However, while a case may achieve an overall SIF impact of one, the SIF impact for each category of indicators (environmental, economic and social) may skew more favourably/unfavourably for each category of indicators relative to the average theoretical pre- and post-retrofit results of the 20 case studies.

Table 4.23: SIF impacts of the retrofit packages from a householder's perspective accounting for the rent increases of the houses.

		Excluding Social Indicator		Including Social Indicator	
Case Study	House Type	Pre-Retrofit	Post-Retrofit	Pre-Retrofit	Post-Retrofit
1	1994-MT	0.54	0.54	0.74	0.72
2	1994-MT	0.76	0.81	0.85	0.94
3	1994-MT	0.89	0.77	0.93	0.85
4	1994-MT	0.91	0.82	0.95	0.92
5	1994-ET	0.78	0.64	1.02	0.82
6	1994-ET	0.80	0.85	0.93	0.90
7	1994-ET	1.04	1.15	1.03	1.10
8	1994-ET	1.04	0.64	1.04	0.77
9	1994-ET	1.17	1.00	1.11	1.00
10	1994-ET	1.40	1.07	1.27	1.05
11	1994-ET	1.50	1.23	1.34	1.15
13	2000-MT	0.50	0.59	0.73	0.74
14	2000-MT	0.51	0.60	0.84	0.74
15	2000-MT	0.76	0.54	0.92	0.82
16	2000-MT	1.08	1.02	1.08	1.01
17	2000-ET	0.34	0.39	1.17	0.66
19	2000-ET	0.56	0.59	0.80	0.72
21	SD-ET	0.61	0.86	1.00	0.93
22	SD-ET	0.68	0.92	0.90	0.96
23	SD-ET	1.65	1.04	1.43	1.03

A SIF impact of less than one means the case study is more sustainable with the most sustainable houses trending towards zero. A SIF impact of greater than one means a house is less sustainable relative to the average theoretical pre- and post-retrofit results of the 20 cases.

From a householder's perspective, a combination of the increased LCCs and energy saving deficits from the retrofit works result in 11 of the 20 households improving their SIF impact without considering the social impact of the retrofit (Table 4.23). The amount of time the average temperature and average relative humidity was within the thermal comfort range as defined in EN 15251 [303] was used as the social indicators. Once the social indicators are accounted for, 16 of the 20 households improve their SIF impact. As can be seen in Table 4.23, four case studies increased their SIF impact following the retrofit. Two of SIF impact increases were due to the household increasing their gas consumption post-retrofit despite already been commonly inside the thermal comfort range pre-retrofit (Case 2 and Case 7) and two other case studies increasing their gas consumption post-retrofit (Case 13 and Case 22).

4.5 Discussion and Conclusions

4.5.1 Are Energy and Cost the Only Environmental Indicators that Need to be Evaluated?

The objective of the theoretical case study presented in this chapter was not to provide an optimal retrofit design solution for all semi-detached houses in Ireland, as the number of case studies examined was not sufficient. The objective was to examine whether the optimum energy efficiency retrofit design differs based on multiple indicators rather than relying on only energy consumption and financial cost. 35 different energy efficiency retrofit packages for a theoretical gas-heated cavity wall semi-detached house were examined using both the cost-optimal methodology and the SIF using multiple indicators from a household and societal perspective.

Using the cost-optimal approach, it was found that without the use of tax breaks and/or grants, only shallow retrofits (attic insulation) were cost-effective for an energy efficiency retrofit. This may be due to the retrofit packages examined as the difference in the shallow and advanced building element U-values was large, and window retrofits are also not recommended in terms of cost payback for houses constructed from the 1980's onwards [20]. However, once government aided grants were considered, deeper energy efficiency retrofit packages became cost-optimal. This highlighted the need for government aid in encouraging deep energy efficiency retrofit of the residential housing stock and why governments should focus on grants and tax breaks to encourage building energy efficiency retrofits rather than paying fines for not achieving energy efficiency and carbon reduction targets.

The cost-optimal methodology and the SIF householder's perspective scenario both found that implementing the basic thermal fabric retrofit measures for all the building elements and introducing a gas boiler or heat pump with renewable energy technology to be the optimum packages (Retrofit Package A-S5(a)/(b)) once grants were considered. Most of the retrofit packages including renewable technology that moved the case study building towards nZEB new build energy standards were found to be the optimum packages once grants were accounted for.

When examined from a societal perspective considering all the evaluated indicators in the SIF, it was found that a gas boiler heating system upgrade following upgrading the building elements was among the lowest SIF impacts. For designing energy efficiency retrofits, the results have shown the importance of considering life cycle environmental indicators and including more indicators other energy and cost when evaluating the sustainability of a building retrofit design. When only considering cost and energy, the ASHP retrofit packages (S4(b) and S5(b)) outperformed many of their gas retrofit package counterpart (S4(a) and S5(a)) in most instances. Conversely, once all the indicators were considered, the gas retrofit packages (S4(a) and S5(a)) outperformed their ASHP retrofit package counterparts (S4(b) and S5(b))

The life cycle energy and life cycle GWP results supported having grants available to householders to install an ASHP and/or renewable technology. However, for other environmental indicators evaluated, heat pumps and adding renewable technology were found to be worse in many instances due to the environmental embodied impact of the systems and the environmental impact of the electricity grid. For retrofit steps S-4(b), S-5(a) or S-5(b), the introduction of an ASHP heating system and/or renewable technology resulted in the larger life cycle ODP, life cycle EP, life cycle AP and life cycle POCP impacts. In some energy efficiency retrofit packages, the embodied environmental impact from the introduction of an ASHP and/or renewable technology accounted for the total life cycle ODP, life cycle EP, life cycle AP and life cycle POCP impact. The environmental impacts can be mitigated through developing more environmentally friendly production processes or recycling the technology at the end of their life span, which was not considered in the analysis.

Due to the ASHP having an efficiency approximately four times that of the gas boiler, an ASHP was better environmentally in terms of operational energy, GWP, ODP and POCP. However, for AP and EP, a gas boiler was found to be less impactful. The analysis found that if Ireland is to continue moving toward a more electrified economy which will increase the demand for electricity, the environmental impact of electricity generation for multiple indicators needs to be continuously monitored and mitigated to ensure Ireland achieves its goal of a sustainable economy by 2050.

In the SIF analysis, a limited number of indicators were assessed, and indicator weightings assumed for the householder and societal evaluations. Further research is needed into selecting appropriate indicators, indicator weightings and an optimization methodology for assessing the sustainability of a building retrofit design. The cost-optimal approach was found to be effective for identifying retrofit packages that are among the best packages even without accounting for multiple environmental indicators. However, once multiple indicators were considered, the hierarchy of the optimal retrofit packages changed. While the cost-optimal method should not be relied on solely for identifying the optimum retrofit package solution, it could be employed as part of the multistage assessment methodology for narrowing down design solution sample sizes such as that employed by Tadeu (2015). Using the remaining array of retrofit packages solutions, the optimum retrofit package could be identified using multiple indicators.

4.5.2 What about the Social Benefits of Energy Efficiency Retrofits?

While partially government funded building energy efficiency retrofit packages may be cost-effective in theory, the actual energy consumption of houses may result in energy efficiency retrofit packages not being cost-effective for a householder. Based on actual gas consumption, only six of the monitored houses which underwent an energy efficiency retrofit would reduce their life cycle costs over 30 years, if 50% of the retrofit work cost was covered by a government grant. SEAI currently offers a government grant of 50% for retrofit works for housing association homes as part of the Better Energy Communities Scheme [301]. For the monitored case studies, the retrofit cost was covered by an SEAI grant with the remaining covered by a rent increase for the householders. Based on the rent increase, only eleven of the households achieved an LCC reduction over 30 years. For the monitored case study buildings in this analysis, an average energy saving deficit of 62% was found ranging from -60% to 152%. Several studies have reported the average energy saving deficits of studies to range from 14% to 98% [45], [46], [55], [47]–[54]. Scheer et al. [45] found a shortfall in energy savings ranging from 28-44% for homes involved in the SEAI Better Energy Homes scheme which provides grants to Irish homeowners for energy efficiency retrofits.

While multiple environmental and economic indicators need to be evaluated for developing a sustainable energy efficiency retrofit design, the energy saving deficits often experienced by residential buildings require social benefits to be evaluated for an energy efficiency retrofit design from a householder and societal perspective. When only considering the economic and energy saving impacts of retrofitting the homes, only 11 of 20 households improved their SIF impact from after the retrofit which may suggest that the retrofitting works should not have been carried out on the housing estate.

Quantifying the social benefits can help to justify cost savings that may not be achieved. The IEA Energy in Buildings and Communities Annex 56 project ([165], [189]) has developed a methodology that employs a matrix of co-benefits expected from retrofit energy efficiency measures for justifying selecting retrofit energy efficiency solutions that go beyond the cost-optimal solution. The benefits are based on the positive and negative experiences and perceptions of building users. While experiences and perceptions of building occupiers are important, it is also important to assess retrofit energy efficiency measures social benefits using quantitative data. Once the thermal comfort social indicators (temperature and RH) were accounted for together with energy and cost, 16 of the 20 households saw a benefit from the retrofit works rather than 11 when not accounting for the social indicators.

Each of the houses received new windows. Window retrofits are not recommended in terms of cost payback for houses constructed in Ireland from the 1980’s onwards [20]. The cost of the windows represented up to 48% of the retrofit costs for some of the houses. The installation of the windows played a key role in the increases in LCC experienced by many of the houses. However, the installation of new windows in the houses was justified as many of the householders complained of the drafts entering their houses from around the windows pre-retrofit. The majority of the householders highlighted less drafts entering the houses post-retrofit resulting in an improved thermal comfort for the householders. Therefore, if cost-effective energy reductions are not being achieved by householders through an energy efficiency retrofit, social benefits experienced by a householder need to be quantified to encourage the uptake in energy efficiency retrofit measures.

Governments need to quantify the benefits from a societal perspective to justify investing money into buildings where energy and cost savings may not be achieved. In Ireland, SEAI in conjunction with the Irish National Health Service are currently examining whether a home energy efficiency retrofit helps in improving the living conditions of people living with chronic respiratory conditions [315].

4.5.3 Government Grant Programmes and Energy Efficiency Research.

Government grant programmes offer a great opportunity for studies to quantify the benefits of energy efficiency retrofit measures and other studies relating to energy consumption. For example, the factors that are driving the differences in energy consumption and energy savings experienced by houses across multiple houses. Take, for example, the monitored case studies in this analysis, where there were five main types of houses within the study. Following the retrofitting of the houses, the gas energy consumption for the different construction types had a large variability. The 1994 mid-terrace household gas consumption ranged from 3432 MJ/m^2 to 5346 MJ/m^2, 4093 MJ/m^2 to 8158 MJ/m^2 for the 1994 end-terrace households, 3610 MJ/m^2 to 7238 MJ/m^2 for the 2000 mid-terrace households, 2443 MJ/m^2 to 5338 MJ/m^2 for the 2000 end-terrace households and 6003 MJ/m^2 to 7395 MJ/m^2 for the 2000 semi-detached households.

The energy savings for some of the households were found to be affected by a desire for a higher thermal comfort. However, estimating how much of the energy savings deficit experienced by the households was accounted for by the desire for a higher thermal comfort was not an objective of this study. Of the reviewed literature, only seven studies detailed how much of the energy savings shortfall is accounted for by temperature take back [48], [51], [141], [146], [316]–[318]. Opinion was divided on the significance of the temperature take back in energy savings shortfall from an energy efficiency retrofit with some estimating impacts ranging from 10% to 82% [48], [316]–[318], while others found the impact to be less than 5% [46], [51], [141], [146]. However, there were issues with the methodologies and results of these seven studies such as (i) limited monitoring periods [46], [48], [319], (ii) small sample sizes [147], (iii) limited details of data collection methodologies [316], (iv) houses receiving different retrofit solutions, [46], [48], [316]–[319], (v) no before and after retrofit data [141], (vi) results based on thermostat settings [141], [317] and temperature spot measurements [51] and no attempts to explain whether changes in temperature are due to the physical retrofit of the building or changes in the behaviour of how the occupants operate their homes [48], [316]–[319]. This area of research needs further study to assess how much temperature take back accounts for energy savings deficits.

Given that multiple technical building characteristics, energy usage practices of building occupants and malfunctioning equipment have been identified as reasons for discrepancies in actual energy usage compared to theoretical energy usage of engineering energy demand models (see Section 2.3) in addition to other studies identifying performance gaps in the thermal fabric performance of building elements and infiltration loss of building [320]–[325], it is not anticipated that temperature take back accounts for the 62% energy demand deficit found for the group of monitored houses in this study.

If additional data was gathered from households receiving government aid for an energy efficiency retrofit on what may be influencing their energy demand and energy savings (or lack of), this would help policies move from a generalised approach to individualised that understands specific groups and their needs, as discussed in Amoruso [326].

In summary, the results of this study find that:

- Deep energy efficiency retrofits are economically feasible in Ireland with aid from government grants and tax breaks for semi-detached gas heated houses in Ireland constructed between 1991 and 2002. Without these incentives, only shallow retrofits are economically feasible.
- The ranking of energy efficiency retrofit designs based on multiple life cycle environmental, cost and social indicators differ compared to optimum designs based on only life cycle energy and cost indicators.

- Savings in terms of energy and GWP support the availability of grants for householders to retrofit with an ASHP and/or renewable technology. However, the embodied environmental impact of an ASHP and renewable technology in terms of ODP, EP, AP and POCP need to be mitigated using cleaner production processes or recycling.
- If Ireland is to continue moving to a more electrified economy which will increase the demand for electricity, the environmental impact of electricity generation for multiple indicators needs to be continuously monitored and mitigated to ensure Ireland achieves its goal of a sustainable economy by 2050.
- For semi-detached gas heated houses in Ireland constructed between 1991 and 2002, the operation of the building has a greater life cycle energy and life cycle GWP impact compared to the materials and technology invested from the retrofit, even if the building does move towards new build nZEB standards. Unless the buildings achieve an nZEB new build standard, the operation of the building has a greater impact compared to the materials and technology invested from the retrofit from a life cycle cost, life cycle AP, life cycle EP, and life cycle POCP.
- Social benefits from energy efficiency building retrofits need to be quantified as the theoretical energy and cost savings from a building energy efficiency retrofit may not be achieved.
- Further research is required to understand what factors are driving the shortfall in energy savings from building energy retrofits. In this study, temperature take back from the householders is found to effect energy savings. However, based on findings from other studies where temperature take back was found to account for energy savings shortfalls ranging from 10% to 82% [48], [316]–[318] or less than 5% [46], [51], [141], [146] in addition to other studies identifying technical building characteristics, energy usage practices and malfunctioning equipment as reasons for the discrepancies in actual energy usage to theoretical energy usage of engineering energy demand models [46], [47], [149]–[152], [50], [53]–[56], [80], [147], [148], temperature take back is not expected to account for all the 62% energy savings deficit experienced by the case study houses.

Chapter 5. Are Energy Efficiency Retrofits Changing Energy Cultures?

5.1 Introduction

As can be seen from the results of the monitored case studies in Chapter 4, the way a household uses energy in the home and the energy savings from a material focused energy efficiency retrofit can vary significantly. While the social impacts from a building energy retrofit can help justify not achieving expected energy savings or retrofitting to a greater energy efficiency standard, it is necessary to understand how and why people use energy within a building to be able to predict environmental and social impacts from a change in a building's technical characteristics. This chapter deploys the heuristic of energy cultures to investigate interrelationships between (i) energy efficiency retrofitting, (ii) domestic energy use, (iii) material conditions, and (iv) social and cultural norms of householders. It carefully operationalises the three key elements of the energy cultures framework (ECF) developed by Stephenson et al. [327], to empirically investigate the impact energy efficiency retrofitting has on energy culture indicators and sustainable related outcomes (building energy use and the internal environment) among inhabitants of the monitored case studies presented in Chapter 4.

A careful operationalisation of the three constitutive elements of energy culture made it possible to empirically investigate (i) the impact energy efficiency retrofitting has on energy cultures and the sustainable related outcomes (building energy use and the internal environment) among inhabitants of urban co-operative social housing units in Ireland and (ii) examine possible relationships between energy efficiency retrofitting, domestic energy use practices, material conditions and the attitudes, perceptions and social norms of householders with regards to the sustainable related outcomes.

The parameters employed in Chapter 5 to examine the interrelationships between the operational energy demand practices in buildings, the people occupying buildings and the materials and technology used in the retrofit of the buildings are depicted in Figure 5.1.

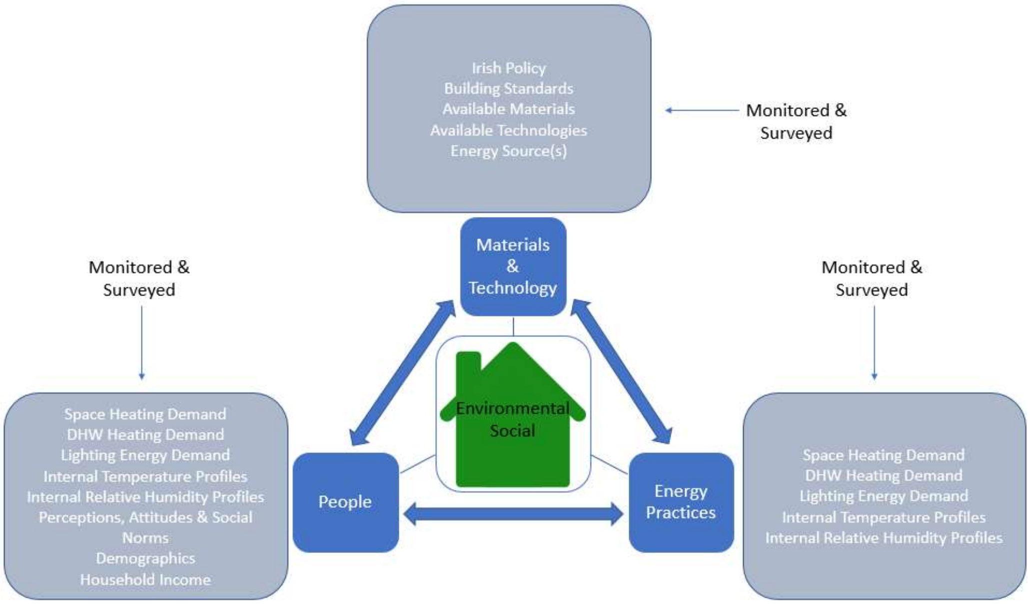


Figure 5.1: The parameters employed in Chapter 5 to examine how the interrelationships between the operational energy demand practices in buildings, the people occupying buildings and the materials and technology used in a building retrofit influence the environmental and social impact of a building retrofit.

The chapter is divided into three sections. Section 5.2 introduces the data collection procedure and how the data analysis is structured using the ECF. Section 5.3 presents empirical data that reflect the three main elements of energy cultures: (i) material conditions, (ii) attitudes, perceptions and social norms concerning energy use, and (iii) energy use practices, as well as selected household characteristics that influence how these three elements manifest themselves within individual households. Changes in energy related attitudes, perceptions and norms at the household level are also presented. In Section 5.4, the benefits and drawbacks of using the ECF for evaluating building retrofits are discussed.

Prof Henrike Rau from Ludwig Maximilian University of Munich and Dr Richard Manton from Engineers Ireland contributed to this chapter in applying the ECF as the framework for investigating the interrelationships between (i) energy efficiency retrofitting, (ii) domestic energy use, (iii) material conditions, and (iv) social and cultural norms of householders and how each of these elements are impacted from a technocentric focused building energy efficiency retrofit. In particular, Prof Rau recommended the ECF as part of the research methodology following a literature review. Prof. Rau and Dr. Manton contributed to the results and discussion for using the ECF for interdisciplinary research to investigate energy efficiency building retrofitting and how it impacts the energy cultures and sustainable outcomes of the households.

5.2 Methodology

5.2.1 Data Collection

To understand how a particular change in material conditions affects householders' attitudes, perceptions and social norms in addition to their energy practices, this analysis draws on very detailed data from 20 households in the monitored case study buildings which underwent an energy efficiency retrofit as described in Section 4.3.2.

To apply the ECF to the analysis of the retrofit, it was necessary to gather data across the three ECF elements using: (i) pre-retrofit and post-retrofit participant surveys, (ii) installation of data-logging instrumentation, and (iii) monthly readings of electricity and gas meters.

First, prior to the retrofitting works carried out in autumn 2015, face-to-face semi-structured surveys were conducted with an adult (aged 18 years or older) in each household. Information was gathered on the demographic profiles of all householders, their attitudes towards energy use and conservation, quality of life and the environment, which items they viewed to be necessities or luxuries, their energy related practices, and their thermal satisfaction within their homes. One year later, participants completed a similar post-retrofit survey, designed to examine changes in each household's attitudes, practices and characteristics. Open-ended questions regarding the householder's attitudes towards the material changes to their house from the energy efficiency retrofit and how it affected their energy consumption were included in the survey. Both surveys used in this study built on an existing lifestyle survey deployed as part of the Consumption, Environment and Sustainability (CONSENSUS) project, an EPA-Ireland funded seven-year collaboration (2009-2015) between the National University of Ireland, Galway and Trinity College Dublin that investigated behaviours and attitudes in four key areas of household consumption [328], [329]. A copy of the survey document used on the residential building householders is given in Appendix E.

Data-logging instrumentation was installed in each of the houses to record characteristics of the indoor environment. Temperature and relative humidity data loggers were placed in multiple rooms. These data loggers were unobtrusive and recorded data at one-hour intervals pre-retrofit and 15-minute intervals post retrofit. Finally, electricity and gas meter readings were recorded once a month for each of the houses. The figures for gas and electricity energy use presented in this chapter correspond to secondary energy and do not account for losses across the network. For the purposes of the analysis, six months of pre-retrofit energy use data (12th February-22nd July 2015) and six months of post-retrofit energy use data (13th February-21st July 2016) have been analysed. Typical monthly average temperatures near the case study site range from 10-16ºC in summer and 4-9ºC in winter (Met Éireann, 2017).

The pre-retrofit and post-retrofit heating season gas usages are normalised using HDDs based on the external temperatures experienced at Dublin airport from February to May during 2015 and 2016 [314]. A base temperature of 15.5°C is assumed in this analysis when calculating the HDDs. The normalised gas usage data (kWh/HDDs) for each phase is multiplied by the average HDDs experienced at Dublin Airport from February to May for 10 years starting from 2005. The following section details the methodology used, including the careful operationalisation of the ECF for data collection and analysis.

5.2.2 Data Analysis Using ECF

While retaining the very useful tripartite structure of the original ECF discussed in Section 2.4, the labels of the three elements introduced by Stephenson et al. [206], [207] are modified. The reasons for this change in terminology are threefold. First, to attempt to retain clear conceptual boundaries between the higher-order 'umbrella concept' of energy cultures and its three constitutive elements it seemed wise to change the term 'material culture' to avoid a two-tier system of cultures where one culture (material) is nested within another culture (energy). Instead, the label 'prevailing material conditions' is used. Second, it was decided to incorporate attitudes and perceptions, as well as social norms, into this study's variant of the ECF. This extends the second ECF element initially referred to as ‘cognitive norms’ in Stephenson et al.’s [206] original work published in 2010 and simply ‘norms’ in their 2015 article [207]. Doing so complements a focus on the rule-governed aspects of energy culture with an emphasis on individual-level views and activities and related aspects of agency.

Following extensive data collection, the resulting empirical material are organised according to the three ECF elements. Complementing the indicators for the three ECF elements, the characteristics of the household and respondents are added to the dataset. These included: number and gender of occupants, hours of occupancy, employment status and household income (as argued in Section 2.4, several of these characteristics are not sufficiently incorporated in the ECF and could moderate the effect of certain ‘systemic influences’, at least at the household level).

For the material conditions element, the physical characteristics of the building, including terrace position, orientation, external walls, attic insulation, windows, and heating systems are considered, in addition to the number of appliances owned by the tenants (see Table 5.2).

Five indicators are selected for the attitudes, perceptions and social norms element (Table 5.2): perceived comfort levels (thermal comfort), perceptions of appliances as necessities or luxuries, desired benefits of the retrofit, preferences concerning incentives and environmental attitudes. A list of ten pro-environmental attitude statements, that mirrored those in the CONSENSUS Lifestyle Survey [328] are used, as listed in Table 5.1. Households could score between 10 and 50 points, with a higher score indicating a stronger pro-environmental attitude. Furthermore, three appliances are chosen for comparison across all households: dishwasher, TV and games console. These appliances are selected because of their availability and because many householders viewed them as a necessity, which made continued ownership and use more likely when compared to other appliances.

Nine indicators represent the practices element of the ECF. The average daily energy consumption is derived from the meter readings for the six-month periods before and after the retrofit, which is disaggregated for gas and electricity.

It was necessary to summarise some of the indicators using categorical frequencies rather than more detailed information. Information about how (often) the householders operated their SH and DHW heating system are represented as qualitative indicators.

Table 5.1: List of environmental attitude statements [328].

List of environmental attitudes statements
I'm willing to sacrifice some comfort to save energy
Everybody has the right to use natural resources according to demand
I'd like to think people see me as environmentally friendly
I feel guilty when I use a lot of energy
Owning a big house is an important goal of mine
Society needs to consume less to protect environment for future generations
I feel morally obliged to reduce energy use
It’s important to use less energy and lower utility use
My quality of life will reduce by decreasing energy use
It takes too much of my time to reduce energy use

To examine the energy cultures of householders in relation to energy consumption, the number of hours lighting is typically turned on, the number of appliances owned by the householders and the frequency of usage of four high electricity consuming appliances (dishwasher, washing machine, tumble dryer and electric shower) are considered.

Other indicators of practices, similar to the examples given in Table 2.7, were collected during the pre-retrofit and post-retrofit surveys, including hours of heating, heating schedule settings, ventilation practices and use of smaller energy consuming appliances. However, these results were only recorded once during both the pre-retrofit and post-retrofit monitoring period, and they may not be fully representative of householders’ practices during the two six-month periods considered.

The energy related outcomes focused on building energy use and the internal environment. The building energy use is represented using the average daily gas and electricity energy consumption derived from the meter readings for the six-month periods before and after the retrofit. For the internal environment, information on the average temperature of the house during the pre-retrofit and post-retrofit heating season periods is given.

Applying the same screening procedure to identify and remove erroneous temperature data as discussed at the end of Section 4.3, comparable temperature data available for the kitchen and living room during the heating seasons of the pre-retrofit and post-retrofit monitoring phases are presented. A two-sample z-test for comparing two means is used for examining whether houses experienced a statistically significant change (95% confidence level) in average house temperature profiles. The percentage of time the average temperature was under the thermal comfort range as defined in EN15251 [303] is also presented pre-retrofit and post-retrofit. Unlike the temperature data presented in Section 4.4 which uses all available comparable non-erroneous data, the temperature data analysed in this chapter is based on temperature data collected from the kitchen and living room of each of the case studies. This is due to this chapter examining potential factors influencing differences in energy consumption and energy savings across the different case studies. Whereas the temperature data analysed in Section 4.4 was to examine if the households experienced a difference in temperature and not to explain the differences in energy consumption and energy savings across the different case studies. In addition, householders were asked whether there was a presence of mould in their home.

5.3 Results

All selected indicators that connect to the three elements of the ECF plus those that capture the energy related outcomes and household characteristics are outlined in the following three tables. Table 5.2 provides an index for the two subsequent tables. Table 5.3 presents the pre-retrofit results for all indicators, followed by post-retrofit results in Table 5.4. Moreover, the colour scheme in Table 5.4 marks any post-retrofit changes, drawing readers' attention to them. The case study numbers are the numbers applied to the case study houses in Table 4.21. The case study results presented in Table 5.3 and Table 5.4 are presented in order of lowest to highest energy consumption for the five main types of houses within the study, as defined by construction year and terrace position.

5.3.1 Impact of Energy Efficiency Retrofit on ECF Elements

The ECF was used to investigate the relationship between the energy efficiency retrofitting and changes in indicators that connect to the three elements of ECF and household characteristics across 20 case studies.

5.3.1.1 Household characteristics

This analysis involved householders with particular employment characteristics, income levels and occupancy numbers, which may affect their responses to retrofitting. Householders' incomes ranged from €14,100 to €65,800. The median real disposable household income in Ireland is €44,782 [330]. The rent of householders living in houses constructed in 1994 increased by €3 per week for five years after the houses were retrofitted. Due to more insulation installed in the external walls of the houses built in 2000 during the retrofit works, the householders living in these houses had a rent increase of €6 per week for five years. This rent increase was to pay for the energy efficiency retrofit works in combination with a grant received through the SEAI Better Energy Communities grant programme [301]. This was not represented in the household income indicator as this represents householders' net income. Working in the service sector (35%), unemployment (20%) and looking after the home (15%) represented the head of household status for a significant portion of households. 17 households stated that on an average weekday, there was someone present in the house 24 hours a day. Only two households reported that the house was unoccupied for 4 hours or more. In all, there were 78 residents (48 female and 30 male) living in the houses, mostly in households of four or five people. Those under 14 years of age represented the largest age group, followed by the category 36-45 years old. 16 of the 20 households have lived in their house for 10 years or more, which suggested that many householders could be particularly routinised in their domestic practices. There were changes for some households in terms of household income and average number of hours the building was occupied in the follow up post-retrofit survey. However, any change in the household characteristics indicators used were not directly related to the energy efficiency retrofit works.

5.3.1.2 Material Conditions

Changes to the building structure and primary heating system were directly related to the energy efficiency retrofit works. Prior to the retrofit works, many householders complained of heat loss, uncomfortably cool indoor temperatures, excess drafts entering via badly sealed windows and doors, condensation on windows and mould growth around window framing and junctions of walls and ceilings. To address these issues, energy efficiency retrofit works included pumped cavity wall insulation, attic

Table 5.2: Index of indicators for each ECF element.

Household characteristics	
# occupants	Number of house occupants
# children	Number of children living in house
Gender	Gender of house occupants: F (female), M (male)
Empl. Status	Employment status of head of household: 1 (employed); 2 (unemployed); 3 (looking after home); 4 (student); 5 (retired); 6 (Other)
Hours occ.	Hours house occupied during typical day
HH income	Household income (including benefits) in €000s
Material conditions	
Constr. Year	Year house constructed
Terrace pos.	House terrace position: Mid (mid-terrace), End (end-terrace), SD (Semi-detached)
Orientation	House orientation: East, West, North, South, South-West
Ext. walls	External walls: HB (hollow block wall for majority of house); CW (cavity wall); PC (pumped cavity wall)
Attic insul.	Attic insulation: 100mm (100mm fibreglass between joists); 400mm (100mm fibreglass between ceiling joists and 300mm glass mineral wool on top of ceiling joists)
Window	W-6 (Wooden frame double-glazed air filled with 6mm gap); P-6 (PVC frame double-glazed air filled with 6mm gap); P-16 (PVC framed double-glazed argon filled with 16mm gap)
Boiler effic.	Gas boiler efficiency: %
2nd heating	Secondary heating system: OF (Open Fire); ST (Solid Fuel Stove); GF (Gas Fire); EF (Electric Fire)
# appliances	Number of appliances owned of: dishwasher, washing machine, tumble dryer, TV, PC, games console, microwave, cooker, electric shower, power shower
Ventilation	Ventilation strategy: A (Passive vents in windows), B (Passive vents in windows and walls); C (Passive vents in windows and walls and mechanical extracts in kitchen and bathroom)
Air-Perm.	Air permeability of building based on a fan pressurization method test carried out to I.S. EN 13829:2000 standards: $m^3/(h.m^2)$@50Pa.

Table 5.2: Index of indicators for each ECF element (continued).

Attitudes, perceptions and social norms	
Thermal comfort	Thermal comfort: VS (very satisfied); S (satisfied); N (neither satisfied nor dissatisfied); D (dissatisfied); VD (very dissatisfied)
Nec. v Lux.	Number of indicator appliances (TV, dishwasher, games console) perceived as necessities
Benefit	Desired/perceived post-retrofit benefit: 1 (reduce your energy bills); 2 (increase in the comfort level); 3 (improve the environment)
Incentives	1 (financial incentives/grants); 2 (lower utility bills); 3 (information/campaigns); 4 (better labelling); 5 (peer support); 6 (none of the above)
Env. Att	List of 10 pro-environmental attitudes statements ([328]; see Table 2); five-point scale: strong agreement (5) to strong disagreement (1)
Practices	
CH freq.	Central heating frequency of usage during winter: 1 (daily); 2 (few times per week); 3 (few times per month); 4 (never)
CH set.	Space heating controller operation settings: PR (space heating controlled with schedule and thermostat); PR/M (space heating controlled with schedule and thermostat and manually operated by householder); M (space heating manually operated by householder)
WH freq.	Water heating frequency of usage during winter: 1 (daily); 2 (few times per week); 3 (few times per month); 4 (never)
WH sec.	Does householder use electrical immersion for domestic water heating: Yes; No
Hrs lights on	Hours lights on inside house on typical day
Dishwasher	Water heating frequency of usage during winter: 1 (daily); 2 (few times per week); 3 (few times per month); 4 (never)
W. Machine	Water heating frequency of usage during winter: 1 (daily); 2 (few times per week); 3 (few times per month); 4 (never)
Tum. Dryer	Water heating frequency of usage during winter: 1 (daily); 2 (few times per week); 3 (few times per month); 4 (never)
Elec. Shower	Water heating frequency of usage during winter: 1 (daily); 2 (few times per week); 3 (few times per month); 4 (never)
Energy related outcomes	
Av. en. daily	Average daily energy consumption (kWh) from February to July: gas and electricity (kWh)
Av. temp.	Average temperature of living room and kitchen from February to May (ºC)
Temp. TC.	Percentage of time the average temperature was inside the thermal comfort range as defined in EN15251 [303] from February to May (%)
Av. RH	Average relative humidity of living room and kitchen from February to May (ºC)
RH. TC.	Percentage of time the average relative humidity was inside the thermal comfort range as defined in EN15251 [303] from February to May (%)
Mould	Is there a presence of mould within the house: Yes; No

Table 5.3: Pre-retrofit performance of households across all three ECF categories. Refer to Table 5.2 for explanations and units for each indicator.

Case Study #	1	3	2	4	5	8	7	11	10	13	14	15	16	17	19	12	20	22	21	23
Household characteristics																				
# occupants	4	4	8	3	1	2	2	4	5	3	4	4	5	2	5	4	4	4	5	5
# children	3	3	6	1	0	0	0	3	4	1	3	3	3	1	3	3	2	2	3	3
Gender	2F, 2M	3F, 1M	5F, 3M	2F, 1M	1M	1F, 1M	1F, 1M	4F	3F, 2M	1F, 2M	4F	2F, 2M	2F, 3M	2F	3F, 2M	3F, 1M	2F, 2M	3F, 1M	2F, 3M	3F, 2M
Empl. status	3	1	1	1	1	5	2	1	1	2	2	3	1	3	6	2	1	1	1	1
Hours occ.	24	24	24	24	20	24	24	24	22	24	20	24	24	24	24	24	24	24	24	24
HH income	17	20	37	36	17	22	17	30	66	18	20	25	33	14	23	19	29	30	34	43
Material conditions																				
Constr. year	94	94	94	94	94	94	94	94	94	00	00	00	00	00	00	00	00	00	00	00
Terrace pos.	Mid	Mid	Mid	Mid	End	End	End	End	End	Mid	Mid	Mid	Mid	End	End	End	End	SD	SD	SD
Orientation	E	E	W	W	S	N	W	W	W	S	S	S	W	S	SW	SW	S	SW	W	SW
Ext. walls	HB	HB	HB	HB	HB	HB	HB	HB	HB	CW	CW	CW	CW	CW	CW	CW	CW	CW	CW	CW
Attic insul.	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Window	P-6	P-6	P-6	P-6	P-6	P-6	P-6	P-6	P-6	W-6	W-6	W-6	W-6	W-6	W-6	W-6	W-6	W-6	W-	W-6
Boiler effic.	79	79	79	79	91.8	79	88.5	91.8	79	77	77	77	77	77	77	77	90.9	77	77	88.4
Boiler Pow.	11.72	11.72	11.72	11.72	19.5	11.72	15	19.5	11.72	10	10	10	10	10	10	10	22	10	10	18.0
2nd heating	OF	N/A	GF	EF	OF	OF	GF	EF	OF	GF	EF	OF	OF	OF	EF	EF	EF	ST	EF	OF
#appliances	8	13	11	12	12	13	8	6	20	11	13	9	11	9	11	13	12	12	19	15
Ventilation	B	B	B	B	B	B	B	B	B	A	A	A	A	A	A	A	A	A	A	A
Air-Perm.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	8.94	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Attitudes, perceptions and social norms																				
Th. comfort	VD	VD	VD	D	VD	S	VD	D	VD	D	D	D	D	VD	VD	VD	S	S	VD	D
Nec. v Lux.	1	1	1	2	0	1	1	1	0	0	1	0	1	2	2	1	3	1	1	1
Benefit	2	1	2	2	2	2	2	1	2	1	2	1	1	2	2	1	2	1	2	1
Incentives	1	1	1	1	3	2	1	2	2	3	3	2	1	1	2	3	2	1	1	1
Env. Att.	35	39	36	44	34	39	33	36	35	38	33	33	37	32	36	34	33	29	32	32

Table 5.3*: Pre-retrofit performance of households across all three ECF categories (continued).*

Case Study #	1	3	2	4	5	8	7	11	10	13	14	15	16	17	19	12	20	22	21	23
Practices (February-July 2015)																				
CH freq.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
CH set.	PR/M	PR/M	PR/M	M	PR/M	PR/M	M	PR/M	PR/M	M	PR/M	M	M	M	PR/M	PR/M	PR/M	M	M	PR/M
WH freq.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
WH Sec.	Yes	No	No	Yes	No	No	No	No	Yes	Yes	Yes	No	No	No	Yes	Yes	No	Yes	No	No
Hrs lights on	14	6	14	6	3	14	14	14	14	6	14	6	6	14	6	14	11	24	14	14
Dishwasher	0	2	3	2	2	2	0	0	3	3	0	0	0	3	3	2	3	3	0	3
W. Machine	3	3	3	0	2	2	2	3	2	3	2	3	2	3	2	2	3	3	3	3
Tum. Dryer	0	1	3	0	1	2	2	2	1	0	0	3	0	2	1	0	1	0	0	3
Elec. Shower	0	3	0	3	0	3	0	0	0	3	0	0	0	0	3	3	3	0	0	3
Energy related outcomes																				
Av. en. daily	26	35	34	41	27	34	44	47	50	27	25	36	40	19	28	32	48	33	33	58
Gas	15	24	21	25	20	27	28	38	33	17	16	20	27	10	18	22	31	20	18	42
Electricity	11	11	13	16	7	7	16	10	16	10	9	15	12	9	9	10	17	12	15	16
Av. Temp.	20.2[1,3]	19.8[2,4]	-	20.7[2]	18.3[1]	20.6[1]	20.1[2,3]	20.6[1,3]	22.0[1]	18.9[2]	19.1[1,3]	18.7[2,4]	20.3[2]	16.9[1]	18.5[1]	-	20.1[1]	18.1[1]	-	21.7[1]
Temp. TC	86	93	-	96	53	99	99	99	100	87	86	75	96	29	64	-	100	61	-	100
Av. RH.	48.4[1,3]	45.9[2,4]	-	40.8[2]	46.7[1]	46[1]	44.8[2,3]	40.8[1,3]	40.0[1]	48.6[2]	44.7[1,3]	50.5[2,4]	43.8[2]	59.1[1]	51.6[1]	-	48.7[1]	52.0[1]	-	42.6[1]
RH. TC	100	100	-	100	100	100	100	100	100	100	100	100	100	100	100	-	100	100	-	100
Mould	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Notes:																				
Temperature data begins from the [1]13th February or the [2]27th February. Temperature data available for only [3]living room or [4]kitchen.																				

Table 5.4: Post-retrofit performance of households across all three ECF categories. Refer to Table 5.2 for explanations and units for each indicator.

Case Study #	1	3	2	4	5	8	7	11	10	13	14	15	16[a]	17	19[a]	12	20[a]	22	21	23
Household characteristics																				
# occupants	4	4	8	3	1	2	2	4	5	3	4	4	5	2	5	-	4	4	5	5
# children	2	3	6	1	0	0	0	3	4	1	3	3	3	1	3	-	2	2	3	3
Gender	3F, 1M	3F, 1M	5F, 3M	2F, 1M	1M	1F, 1M	1F, 1M	4F	3F, 2M	1F, 2M	4F	2F, 2M	2F, 3M	2F	3F, 2M	-	2F, 2M	3F, 1M	2F, 3M	3F, 2M
Empl. status	3	1	1	1	1	5	2	1	1	2	2	6	3	3	6	-	1	1	1	1
Hours occ.[b]	21	24	24	22	16	24	24	24	24	24	20	24	23	24	24	-	24	22	24	24
HH income[c]	16	22	37	36	25	22	16	20	66	18	20	24	33	14	30	-	29	29	34	43
Material conditions																				
Ext. walls	HB	HB	HB	HB	HB	HB	HB	HB	HB	PC	PC	PC	PC	PC	PC	PC	PC	PC	PC	PC
Attic insul.	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400
Window mm	P-16	P-16	P-16	P-16	P-16	P-16	P-16	P-16	P-16	P-16	P-16	P-16	P-16	P-16	P-16	P-16	P-16	P-16	P-16	P-16
Boiler effic.	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3
Boiler Power	17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8
2nd heating	OF	N/A	GF	EF	OF	OF	GF	EF	OF	GF	EF	OF	OF	OF	EF	-	EF	ST	EF	OF
# appliances	8	13	11	13	12	16	8	9	17	13	12	15	10	11	16	-	15	9	13	12
Ventilation[d]	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Air-Perm.	N/A	N/A	N/A	N/A	8.75	7.28	N/A	8.86	8.59	N/A	N/A	5.93	N/A	N/A	N/A	-	5.46	5.91	N/A	6.36
Attitudes, perceptions and social norms																				
Th. Comfort[e]	D	VD	D	N	N	VS	S	D	VS	S	S	S	S	VS	S	-	S	VS	D	S
Nec. v Lux.[f]	1	1	1	2	0	1	1	1	1	1	0	0	2	2	1	-	3	1	1	2
Benefit[g]	1	2	2	2	2	2	1	1	2	2	2	2	1	2	2	-	2	2	1	2
Incentives[h]	3	4	2	2	3	2	2	2	1	1	3	2	3	1	2	-	1	2	1	2
Env. Att.[i]	33	37	34	42	35	37	32	35	31	30	37	37	37	34	36	-	29	29	32	32

Table 5.4: Post-retrofit performance of households across all three ECF categories (continued).

Case Study #	1	3	2	4	5	8	7	11	10	13	14	15	16[a]	17	19[a]	12	20[a]	22	21	23
Practices (February-July 2016)																				
CH freq.[j]	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	-	1	1	1	1
CH set.[k]	PR/M	PR/M	PR/M	PR/M	PR/M	PR	M	M	PR/M	M	PR/M	PR/M	M	M	PR/M		PR/	M	PR/	PR/M
WH freq.[j]	1	2	1	1	1	1	4	1	1	2	1	1	1	1	2	-	1	1	1	1
WH Sec.[j]	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	-	No	No	No	No
Hrs lights on[l]	8	7	14	6	6	14	5	15	6	7	15	6	6	14	6	-	14	24	14	14
Dishwasher[j]	0	2	3	2	2	2	0	0	3	3	0	0	0	3	3	-	3	3	0	3
W. Machine[j]	2	3	3	0	2	2	3	3	2	3	2	3	2	3	2	-	3	3	3	3
Tum. Dryer[j]	0	1	3	0	2	2	1	2	1	0	0	3	0	2	1	-	2	0	2	3
Elec. Shower[j]	0	3	0	0	0	3	0	0	0	3	0	0	0	0	3	-	3	0	0	3
Energy related outcomes																				
Av. en.	18	27	30	27	24	23	39	36	36	24	22	26	35	20	25	25	36	33	31	41
Gas[m]	11	18	18	19	16	16	26	27	24	15	14	13	22	10	16	13	20	22	19	25
Electricity[m]	8	9	12	8	8	7	12	9	12	9	8	14	12	9	10	12	16	11	12	16
Av.Temp.[n]	20.3[1,3]	20.6[2,4]	-	19.2[2]	19.1[1]	19.7[1]	21.0[2,3]	20.4[1,3]	21.7[1]	20.1[2]	19.9[1,3]	17.2[2,4]	20.7[2]	19.4[1]	20.2[1]	-	-	19.	-	22.6[1]
Temp. TC[o]	93	96	-	82	72	96	100	100	100	97	99	46	99	89	100	-	-	96	-	100
Av. RH.[n]	48.8[1,3]	49.2[2,4]	-	45.5[2]	46.3[1]	46.1[1]	45.1[2,3]	42.7[1,3]	46.2[1]	48.3[2]	45.7[1,3]	54.2[2,4]	47.9[2]	52.2[1]	47.2[1]	-	-	48.	-	45.7[1]
RH. TC[o]	100	100	-	100	100	100	100	100	100	100	100	100	100	100	100	-	-	100	-	100
Mould[p]	Yes	No	Yes	No	No	No	No	Yes	Yes	No	Yes	No	No	Yes	No	-	Yes	Ye	No	No

Notes

[a]Change of respondent between pre-retrofit and post-retrofit surveys

Blue highlights show changes from pre-retrofit to post-retrofit for household characteristics: [b]>1 hour; [c]>€1k.

Grey highlights indicate changes from pre-retrofit to post-retrofit for: [d]change in ventilation elements; [f]opinion on appliance necessities and luxuries; [g]incentives to encourage retrofitting; [h]benefits from retrofit and [k]change in space heating method.

Green highlights indicate positive pre-retrofit to post-retrofit changes: [e]change in thermal comfort; [i]>2 points up; [j]reduction in energy intensive practice; [l]>1 hour up; [m]>6 kWh (total) / 4 kWh (gas) / 2 kWh (electricity) down; [n]statistically significant increase in average temperature or relative humidity; [o]>5%; [p]reduction in mould.

Red highlights indicate negative pre-retrofit to post-retrofit changes: [e]change in thermal comfort; [i]>2 points down; [j]increase in energy intensive practice; [l]>1 hour down; [m]>6 kWh (total) / 4 kWh (gas) / 2 kWh (electricity) up; [n]statistically significant decrease in average temperature or relative humidity; [o]<5%; [p]increase in mould.

Temperature and relative humidity data available from the [1]13th February or the [2]27th February.

Temperature and relative humidity data available for only [3]living room or [4]kitchen.

insulation, double-glazed uPVC-framed windows, uPVC-framed front door, uPVC-framed back patio doors and heating system and controls as detailed in Section 4.3.2. In addition, to help combat the issue of mould growth within the houses and provide clean, fresh air to the householders, mechanical extract fans were installed in the kitchen and bathroom of each house. Furthermore, passive vents were installed in each room of the houses constructed in 2000 and existing vents were cleaned in the 1994 houses. All the new windows had passive vents along the edging of the window frames.

The impact of workmanship can also be found in the air permeability results of the houses post-retrofit. An air permeability test measures the air leakage rate per hour per square meter of building envelope area at a test reference pressure differential across the building envelope of 50 Pascal. Eight of the 20 households had air permeability tests carried out post-retrofit by an independent contractor. For the end-terraced and semi-detached houses constructed in 2000, theoretically they should have the same level of air-permeability. However, the results ranged from 5.46 $m^3/(hr.m^2)$ to 6.36 $m^3/(hr.m^2)$. For the 1994 end terraced houses, the air permeability post-retrofit test results ranged from 7.28 $m^3/(hr.m^2)$ to 8.86 $m^3/(hr.m^2)$. Unfortunately, only one of the case study houses had an air-permeability test carried out pre-retrofit. Case study 15 improved its air-permeability from 8.94$m^3/(hr.m^2)$ to 5.93 $m^3/(hr.m^2)$. The upper limits of air permeability for houses constructed to 2011 [24] and 2019 [19] residential building energy performance regulations in Ireland are 7$m^3/(hr.m^2)$ and 5$m^3/(hr.m^2)$, respectively.

The pre-retrofit number of appliances in each of the 20 households varied between 6 and 20 and it was possible to detect some significant post-retrofit changes (e.g. household 12 gained six appliances, while household 19 lost six). However, only one household increased the number of high-energy usage appliances, such as the dishwasher, washing machine, tumble dryer, electric shower, microwave or cooker.

As part of the data collection process, Owl +USB [331] and Efergy E2 with USB [332] electricity consumption data loggers were installed to monitor the electricity consumption profiles of the householders pre-retrofit and post-retrofit. The electricity consumption data loggers were left out of sight of the householders and the householders were not taught by the researchers how to use the instrumentation to examine the energy demand of different appliances in the house. However, after one of the householders in Case 4 noticed the large energy demand of both the electrical shower and electrical immersion from the electricity meter, they removed their electrical shower and stopped using their electrical immersion.

5.3.1.3 Attitudes, perceptions and social norms

Before the retrofit, 85% of the households reported being (very) dissatisfied with the warmth of their home, highlighting the poor pre-retrofit thermal conditions of the houses. However, this figure fell to 26% post-retrofit, suggesting a dramatic increase in perceived thermal comfort following improvements in material conditions. When discussing the thermal comfort improvements with the householders, many noted less drafts through the windows and doors as one of the main reasons for the improvement in their thermal comfort. In addition, many felt their house was able to retain heat better than before the retrofit, particularly those living in the houses constructed in 2000 which received cavity wall insulation to the exterior wall.

However, some noted that the issue of drafts had not being entirely eradicated when answering the survey question regarding their satisfaction with the installed retrofit measures. Some felt that drafts were still entering their houses through poorly sealed windows and doors, particularly on windy days. The quality of how the windows and doors were sealed may partly explain the difference in air-permeability in the end terraced houses constructed in 1994, in addition to the end terraced and semi-detached houses constructed in 2000. The new vents that had been installed also came in for criticism regarding drafts. The vents in the walls exposed to prevailing winds were highlighted in particular for their issues with drafts entering the houses leading to some householders closing or blocking them. Issues with post-retrofit drafts from vents in Irish residential buildings leading to householders blocking or closing vents have also been found in another Irish building retrofit study [333].

Others issues with the passive and mechanical extract vents that had been installed were also highlighted by some of the householders. With the mechanical extract fans installed in the kitchen and bathroom, some householders switched them from automatic to manual as it would take them a ‘long time’ to turn themselves off after using the shower in the bathroom or cooking in the kitchen. The kitchen extractor came in for particular criticism as some householders stated the fan in the extractor would be ‘shaking’ and ‘noisy’ during windy weather leading to some blocking it off.

Another issue some householders had with the energy efficiency retrofit technology installed in their houses was the functionality of the new gas boiler heating system. Using the old gas boiler heating system, the householders could operate the space heating and domestic hot water heating system simultaneously. With the new gas boiler heating system, the householders could not operate the SH and DHW heating systems simultaneously. If both the SH and DHW heating systems are operated simultaneously, the DHW takes precedence over the SH. This constraint meant that householders had to adapt their approach to operating their heating system. The functionality of the new gas boiler heating system led to five households (Case 1, 5, 11, 20 and 21) believing they were operating their new gas boiler system more than with the old gas boiler system.

The householders’ pre-retrofit dissatisfaction with the warmth of their homes was reflected in their desired benefit from the retrofitting. ‘Increases in comfort level’ was the top desired benefit for 63% of the households before the retrofit. When quizzed which benefit they perceived to have experienced the most from the retrofit, 74% believed that ‘increases in comfort level’ to have been the main benefit of the retrofit works.

Concerning incentives, participants predominantly chose economic incentives (84% pre-retrofit, 74% post-retrofit) as the best way to encourage people to save energy. Following the retrofit, there was a marked shift away from a preference for grants to lower utility bills. This most likely reflects the fact that grants incentivise once-off pro-environmental behaviour (such as a retrofit, which the participants have already undertaken), while lower utility bills can be achieved by practicing more habitual pro-environmental behaviour [334].

Regarding environmental attitudes, participants generally agreed that it is important to use less energy and that society in general needs to consume less to protect the environment. However, while most of the households agreed that it does not take too much time to reduce energy use, there was a lower level of agreement regarding the sacrifice of comfort, and whether a reduction in energy use lowers quality of life. The environmental attitudes of three households improved by 4 points or more. Two household's attitudes worsened by four points following the retrofit. However, environmental attitudes remained similar across the other 15 households after the retrofit.

There was only a marginal change in attitudes post-retrofit whether householders considered a selection of appliances (TV, dishwasher and games consoles) to be necessities or luxuries in their lives. The majority of the participants deemed just one of these to be a necessity – and this was generally the TV. Unsurprisingly, the one household which considered all three appliances to be necessities owned one of the largest number of appliances overall, including four PCs and two games consoles. It was not expected that any changes in attitudes were due to the energy efficiency retrofit works.

5.3.1.4 Practices

While the functionality of the new gas boiler system meant householders had to adapt to heating the space and DHW separately, the method of how the householders operated their space heating system remained largely unchanged. Before changes to the material conditions, 12 of the householders used a combination of a schedule and manual operation for operating the space heating system. The remaining householders operated the space heating system manually. Only five households changed their heating operation method following the retrofit. Three households changed from manually operating the space heating system to using a combination of a heating system schedule and manual operation.

For space heating, the householders had the ability to set heating schedules with the old and new heating system controller. The added functionality of the new heating system controller allowed householders to set a temperature setpoint for when the space heating should switch off. The household of Case 8 changed to a heating schedule that was programmed to operate for 14 hours a day. However, the householders made use of the added functionality of the thermostat to control the temperature level of the house and when the heating should switch on/off. Many householders set the thermostat setting at a high temperature level. This essentially removed the added functionality of using the thermostat in the hallway to control the temperature of the house and when the boiler switches on/off. Many of the householders justified having a high temperature setpoint by either stating they were advised to operate the heating system using this method by the heating control installers or the temperature profile across the rooms of the house was not uniform.

For the water heating system, eight of the households complemented the main water heating system using the electrical immersion in the hot water tank before the retrofit works. Some of these householders found that it was quicker to use the electrical immersion rather than relying on the gas boiler to heat the hot water. Following the retrofit, none of the households used the electrical immersion for domestic hot water needs.

There was no significant change in the frequency of how householders operated four high electricity consuming appliances except for Case 4 due to the removal of their electric shower as previously discussed.

5.3.1.5 Energy Related Outcomes

Before the energy efficiency retrofit, the average daily energy use of the 20 case study houses was 35.7 kWh/day, constituting two-thirds gas usage and one-third electricity usage. Following the retrofit works, average energy use fell by 19% to 28.9 kWh/day. 18 of the 20 households decreased their energy consumption following the retrofit with 10 households reducing their average daily energy consumption by more than 6 kWh/day.

After the retrofit, 17 of the households reduced their gas energy consumption with 11 households decreasing their average daily gas consumption by more than 4 kWh/day (Figure 5.2). 16 of the households reduced their electricity energy consumption with 6 of the households decreasing their average daily electricity energy consumption by more than 2 kWh/day (Figure 5.3).

There was a 23% decrease in the average daily gas consumption to 18.2 kWh/day. Ideally, this analysis would have a control group of houses that did not receive energy efficiency retrofit measures to compare their change in energy use, attitudes, perceptions and social norms between 2015 and 2016. Unfortunately, this was not feasible. However, 17 of the 20 houses experienced a reduction in HDD corrected gas energy consumption. The overall reduction in energy consumption by the houses was opposite to Ireland's residential energy consumption which increased in 2016 compared to 2015 and 2014 [43]. Therefore, the change in gas energy consumption was likely due to the energy efficiency retrofit works. While the gas energy consumption reduced overall, there remained a substantial range between the lowest and highest gas users and the energy savings for each of the householders (Figure 5.2).

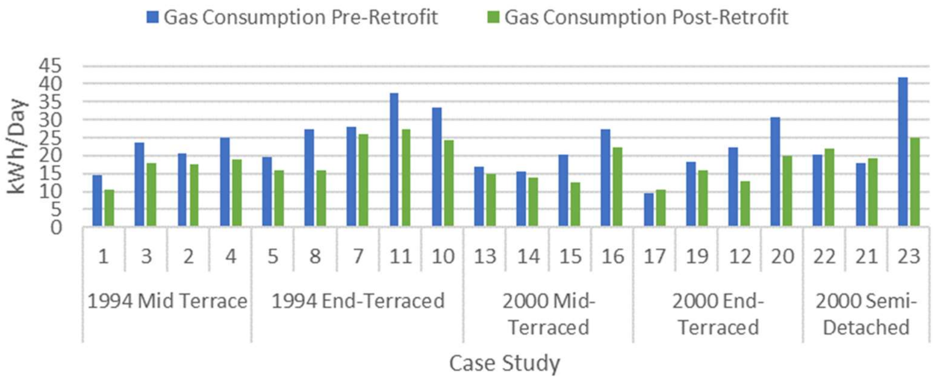


Figure 5.2: Gas consumption of case study houses pre-retrofit and post-retrofit.

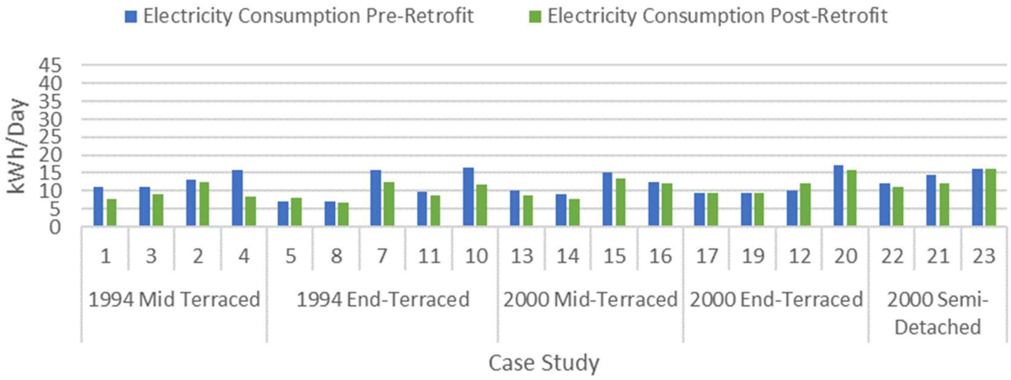


Figure 5.3: Electricity consumption of case study houses pre-retrofit and post-retrofit.

Electricity usage fell by 12% to 10.7 kWh/day. However, as the retrofit energy efficiency works focused primarily on the thermal fabric efficiency of the houses and the gas fuelled primary heating system, the reduction in electricity consumption cannot be attributed to the energy efficiency works.

10 of the cases increased their average temperature by a statistically significant margin. The largest temperature increase was in Case 17 which experienced a temperature increase of 2.5ºC. Case 15 had the largest temperature decrease, dropping by 1.6ºC. The cases who increased their temperature experienced an increase of, on average, 1.1ºC and those who dropped in temperature experienced a decrease of, on

average, 0.8ºC. The cases, on average, increased the average temperature by 0.4ºC. Temperature changes from other energy efficiency building retrofits [48], [51], [141], [146], [316]–[319] reported the average change (excluding confidence intervals) in house temperatures ranged from -0.3°C to 2.8°C with the (i) type of energy efficiency retrofit, (ii) room of house monitored, (iii) period analysed, (iv) heating system employed, (v) household income levels and (vi) householder comfort impacting the level of change in temperature.

Before the retrofit, the range for the percentage of time the house average temperature was inside the thermal comfort limit ranged from 29% to 100% with an average of 88%. Seven of the households improved the percentage of time (>5%) the house average temperature was inside the thermal comfort limit. The percentage results ranged from 46% to 100% with an average of 94%.

17 of the 20 households indicated a presence of mould in their homes before the energy efficiency retrofit. 11 of the 17 households with mould before the retrofit did not have mould afterwards. Mould growth around the frames of the windows had largely disappeared but condensation on the windows remained as an issue.

Issues of mould along the junctions of ceilings and walls persisted. See Figure 5.4(a) for an example of mould along the junction of a wall and ceiling in one of the case study houses. In fact, two additional houses reported issues of mould growth along the mould along the junctions of ceilings and walls in the bathrooms despite the new extractor fan being installed. Due to the building element construction details used in the houses constructed in 1994 and 2000, the junctions of the external walls with other building elements had thermal bridging issues. See Figure 5.4(b) for an example of thermal bridging along the junction of a wall and ceiling causing cold spots in one of the case study houses. The thermographic image was taken using a FLIR T335 thermal imaging camera. Unless householders were diligent with their heating and ventilation strategies to prevent the build-up of moisture in their houses, the moisture in the air would condense on the cold spots along the junctions of the walls with other building elements leading to mould growth.

Figure 5.4: (a) Presence of mould along the junction of a wall and ceiling in a case study house and (b) a thermographic image of the wall and ceiling junction.

The quality of the workmanship for constructing or installing building materials can also lead to thermal bridging. See Figure 5.5**Error! Reference source not found.**(a)-(b) for the worst case of mould along the junction of the external wall and ceiling in the monitored case studies post-retrofit. In this example, the quality of the workmanship lead to a large cold spot area on the ceiling. Based on Figure 5.5**Error! Reference source not found.**(b), the insulation above the ceiling plasterboard does not appear to have been installed correctly. Other issues that may have caused this cold spot are excessive drafts entering through poorly sealed windows or through the eaves in the roof overhanging the external wall of the house. Either way, all these potential issues are symptoms of poor workmanship.

Figure 5.5: (a) Presence of mould along the junction of a wall and ceiling in a case study house and (b) a thermographic image of the wall and ceiling junction.

5.3.2 Interplay of ECF Indicators, Energy Consumption and Energy Savings

The ECF was used to understand how the cultural formations and household characteristics influenced the energy related outcomes across 20 households. Building physics played a role in the energy savings achieved by the households from the change in materials conditions. The top six reductions in gas usage were all experienced in end-terraced or semi-detached houses. However, the people living in the houses also played a key role in the energy savings with the two lowest energy savers also living in semi-detached houses.

Using the tripartite structure of the ECF, it was possible to identify demand-side factors that may have influenced the energy consumption and the success (or lack thereof) of the retrofitting efforts in reducing energy consumption. Despite similar material conditions for main space and water heating for each of the house types, social conditions for households appeared to be influencing energy consumption. Household income appeared to be constraining some of the householders' ability to achieve their perception of a satisfactory thermal comfort level as four households among six of the lowest gas consumers were also among six of the lowest income households. The desire of these four households for a more satisfactory thermal comfort level was realised with improved average temperature. That being said, the household (Case 11) with the joint fifth lowest household income post-retrofit had the largest post-retrofit gas usage. Households with higher incomes may not have been as constrained as other households in the money available for spending on energy as the two highest energy consuming households (gas and electricity) also had the highest income levels.

The influence of the quality of the workmanship on the energy usage levels was difficult to assess as a limited number of households had air-permeability tests carried out. Even for the end-terraced houses constructed in 1994 and the end-terraced/semi-detached houses constructed in 2000 with air-permeability test results, the difference in profiles of the householders in terms of their time spent at home, income levels and how much of their gas usage was for space heating and DHW heating made cross comparisons difficult. However, the 1994 end-terraced house with the highest air-permeability had the highest post-retrofit gas usage (Case 11). The 2000 end-terraced/semi-detached house with the highest air-permeability had the third highest post-retrofit gas usage (Case 23). Case 23 had the highest average indoor temperature and Case 11 had the 6th highest indoor temperature.

The perception of what is a satisfactory thermal comfort level can vary from household to household. For example, the average house temperature for three of the 10 households who were very dissatisfied with their thermal comfort did not fall outside the temperature thermal comfort limit as defined in EN15251 [303] before the retrofit (>1%) (Cases 2, 7 and 10). The perception of what is a satisfactory thermal comfort level may have also influenced the success of the retrofitting efforts in reducing energy consumption. Cases 7 and 8 were (i) 1994 end-terraced housing, (ii) had similar gas consumption and average house temperatures pre-retrofit and (iii) both had two people living in the house. However, the two houses differ on whether they were satisfied with their thermal comfort level. The householders in Case 8 were satisfied pre-retrofit with their thermal comfort level. These householders achieved the second highest gas energy reduction while also slightly reducing their average house temperature. The householders of Case 7 were very dissatisfied with their pre-retrofit thermal comfort level. Following changes to the material conditions, their average house temperature increased by 0.9°C and the household achieved only the 16th highest gas reduction.

Methods of how householders operated their space heating system persisted in many of the households following the retrofit. The hierarchy of houses in terms of gas and electricity energy consumption levels also remained relatively unchanged (position changed by less than three positions) for many of the houses following the energy efficiency retrofit works. Householders changing how they operated their space heating system following the energy efficiency retrofit appeared to have a large impact in terms of the hierarchy of energy consumption among householders. The gas consumption hierarchy position changed by more than three places for five households. Interestingly, three of these five households altered how they operated their space heating system (one of the five households included Case 12 where no post-retrofit survey was carried out). The position of Case 8 and 21 both changed by eight positions. The household of Case 8 had the second highest gas energy savings leading to having the eight lowest gas consumption post-retrofit. This household changed their method of using the space heating system by completely relying on the thermostat controller in the hallway to control their indoor temperature levels and gas boiler operation.

The household of Case 21 on the other hand increased their gas consumption following the retrofit resulting in them having the eight highest gas consumption. The householders of Case 21 changed from manually operating their space heating system to using a combination of a schedule and manual operation. The householders of Case 15 also changed from manually operating their space heating system to using a combination of a schedule and manual operation. However, they improved their position by five places to having the 18th lowest gas consumption. Case 15 also had the largest decrease in household temperature.

The functionality of the new gas boiler heating system whereby both the SH and DHW heating could not be heated simultaneously led to five households believing this constraint meant they were operating their new gas boiler system more than with the old gas boiler system. Of the five households who believed they were using the gas boiler more, three households reduced their gas consumption post-retrofit by more than 4 kWh/day (Case 1, 11 and 20), one household's gas usage reduced by 3.7 kwh/day (Case 5) and one household's gas usage increased by 1.4 kWh/day (Case 21). Unfortunately, the indoor temperature of Case 21 post-retrofit is unavailable to check whether their increased gas usage led to a higher indoor temperature. However, without comprehensive monitoring of the gas boiler disaggregated energy usage profile before and after the retrofit works, it is difficult to assess whether the new functionality of the heating system impacted the energy savings potential of the householders.

In terms of the hierarchy of electricity consumption, seven households changed position by more than three places with four of the seven households not using their electrical immersion to heat their water anymore. Before the retrofit works, the householders of Case 4 found that it was quicker to use the electrical immersion rather than relying on the gas boiler to heat the hot water. Changing the material condition of the gas boiler from 11.7 kW to 17.8 kW allowed the householders to stop using the electrical immersion for heating the water. The householders of Case 4 also stopped using their electric immersion and removed their electrical shower when they discovered the amount of electricity it used. They discovered this from the feedback they received from an electricity consumption in house display installed in their home.

There was no correlation between the number of appliances, householder's attitudes on whether appliances were necessities or luxuries and their electricity energy consumption. However, this may be due to the small sample size of houses involved in this analysis. The electricity consumption may be more related to the nature and frequency of how appliances were used in homes given that the highest electricity consumer during the pre-retrofit and post-retrofit monitoring period was the only household to have reported commonly using the dishwasher, washing machine, tumble dryer and electric shower every day.

5.4 Discussion and Conclusions

5.4.1 Using the ECF for Interdisciplinary Research to Investigate Energy Efficiency Building Retrofitting: Advantages and Drawbacks

The benefits of using the ECF to organise the empirical material and findings of this interdisciplinary energy research were considerable, especially given its focus on the multi-method investigation of a small number of households. Its relative simplicity, easy-to-understand terminology and focus on both social and material aspects of energy use made it an ideal tool for fusing insights from the social sciences, engineering and architecture. At the same time, the ECF was capable of connecting a higher-order theoretical approach (energy cultures) to concrete empirical energy related outcomes. By explicitly recognising the combined impact of infrastructural-material and social conditions on how and why individuals engage in activities or use services that require energy, the ECF offered a credible alternative to monocausal explanations of energy use. Finally, the tripartite structure of the ECF drew attention to the impact of a significant change in the material conditions on socio-cultural aspects of domestic energy use, including shifts in householders' perceptions concerning energy, novel forms of post-retrofit energy use, and evidence of pre-retrofit habits and routines that persisted following the retrofit. Overall, there are ample reasons to extend the use of the ECF into the emerging field of interdisciplinary pre- and post-retrofit studies (for example, Long et al. (2014); Tweed (2013)).

Concerning drawbacks, defining clear boundaries between energy cultures at different scales (e.g. household energy cultures vis-à-vis community energy cultures) can be difficult. For example, some of the systemic influences on energy cultures outlined in Figure 2.1 only acquire the label 'systemic' if the focus of the work lies on energy cultures located at the supranational level. If one were to compare national-level energy cultures, some of these would probably be absorbed into the ECF.

Second, the distinction between the three constitutive elements may be less clear-cut given the close interactions between them. For example, prevailing norms concerning the meaning and use of particular appliances (e.g. dishwasher, smartphone) are directly related to their availability (material conditions), and vice versa [212]. Third, the related issues of energy use *outside* the home are particularly pertinent if treated as part of the picture. In fact, it is entirely unclear whether financial savings made by householders following the retrofitting of their homes are spent on more or less energy-intensive activities. For example, some householders may eventually spend their post-retrofit savings on goods and services that require significant input of energy and other resources (e.g. car, foreign holiday). Only an overall cultural shift that extends beyond energy to include other types of resource use (e.g. water, food, plastics) could prevent this. However, there is no evidence that such a shift has occurred following the retrofitting assessed in this analysis.

Furthermore, challenges were encountered that relate to the nature of the ECF itself, as well as its ‘translation’ into quantitative indicators. As mentioned previously, the ECF can serve as a suitable common ground or ‘shared language’ in multi- and interdisciplinary projects that bring together researchers with diverse theoretical orientations. However, this may also result in a reduction in theoretical nuance that potentially limits the (re-)integration of valuable insights from ECF-based empirical studies into broader social-theoretical debates concerning energy use, including other work on energy cultures. The fact that the original ECF shares some of the terminology with other theoretical and conceptual approaches in social-scientific energy research may cause some confusion, a possibility that informed the decision to modify some of the terms used to describe its elements.

5.4.2 Changing Energy Cultures? Critical Reflections Concerning the Use of the ECF in Pre-Retrofit and Post-Retrofit Assessments

Did the energy efficiency retrofit initiative presented achieve energy savings and improve people’s living conditions as a result? And was there a real shift in household energy cultures following the retrofit programme, extending beyond a linear link between improved material conditions and reduced energy use? The data revealed changes in energy use before and after the material retrofit in the 20 households under study. Reductions in total energy use by 19%, gas use by 23% and electricity use by 12% represent a moderate, yet positive outcome, especially given the economic vulnerability of many of the participating households and their limited capacity to cope with increases in energy prices. Perhaps more importantly, many householders were able to increase the average temperature of their houses, which in turn increased their thermal comfort dramatically. However, this increased comfort level absorbed further potential energy savings. In that sense, the change in practices (ECF Element 3), caused by the change in material conditions (ECF Element 1) brought about huge improvements in thermal comfort, which had been a source of considerable dissatisfaction and discomfort prior to the retrofitting initiative (ECF Element 2). The households showed a strong desire for improved thermal comfort yet were previously constrained by the poor thermal and air infiltration qualities of their houses and/or income levels. These three features mirror conditions in social housing in Ireland more generally, whereby residents spend longer amounts of time in the home, have lower disposable income and typically poorer quality housing.

There was no marked shift in other areas of energy culture, however, pointing to the relative resistance to change of attitudes and social norms and well-established routine practices. In fact, there is some indication that many householders maintained many of their daily practices after the retrofit, including the use of lighting and appliances. For space and domestic hot water heating, householders had to adapt to the functionality of the new gas boiler heating system. While the new system forced the householders to operate the space and hot water heating separately, many of them continued to rely upon the same way of operating the heating system by either a manual or a set programme in combination with a manual approach. This said, some householders switched their water heating practices from the electric immersion to the gas boiler. In sum, changes in material conditions (retrofit) did indeed bring about modest changes in practices and related patterns of energy use; however, the retrofit certainly did not shift prevailing energy cultures in any fundamental way.

The decision to use the ECF as a heuristic for structuring the data collection and analysis also helped to widen the rather narrow focus on material conditions that has limited many pre-retrofit and post-retrofit assessment studies to date. The ECF has also been very useful for identifying potential reasons for varying levels of gas and electricity use across the 20 households under study. While qualitative indicators, energy use data and house temperatures are useful for identifying potential reasons for differences in actual energy consumption and energy savings across households, more in-depth disaggregation analysis of house energy consumption and temperature profiles is required to explain the exact reasons for differences in domestic energy consumption and savings across households.

In this analysis, the focus was on the energy cultures and their energy related outcomes of 20 co-operative social housing units and the tenants of the housing units. However, external influences (Figure 2.1) which were barriers to householders changing their energy cultures were not included as it was not the focus of the analysis. For the households involved in the study, the association which own the housing units play a role in the householder's material conditions. The co-operative housing association which own the housing units applied for the retrofit grant which paid for the majority of the retrofit work. The housing association did not give any of the householders a choice in getting the retrofit or what retrofit technology was installed. Furthermore, some householders stated they were interested in installing energy saving measures to their homes before the energy retrofit work. However, the householders did not as they do not own the house and are not allowed to make any alterations to the exterior of the building ruling out some potential energy saving measures. A common problem with householders in rented housing [226]. Examining the role landlords and property managers play in limiting householders in rented housing investing in energy efficiency measures could be the focus of future research.

In addition, future application of the ECF could be to identify potential reasons for the shortfall in energy saving predicted by engineering models. For example, for the set of households analysed in this study, DEAP would not account for householders changing their water heating habits by not using the electric immersion anymore in estimating energy savings. For five of the eight households who stopped using their electrical immersion, their gas consumption during the non-heating season months increased despite the installation of a more energy-efficient gas boiler and hot water tank. DEAP also calculates the energy demand of houses based on a calculated internal temperature profile. Cases 13, 14 and 15 were all mid-terrace 2000 houses with the same orientation and would have similar average temperatures if assessed using DEAP. Nevertheless, the average post-retrofit heating season temperature profiles of these three cases ranged from 17.2ºC to 20.1ºC. Case 22 and 23 were built side by side, yet their average temperatures during the post-retrofit heating season were 19.8ºC and 22.6ºC, respectively.

In summary, the results of this research find that:

- The ECF is effective in framing interdisciplinary research on energy use before and after retrofitting. Its conceptual focus on both technical-material and social elements matches current efforts to improve the energy performance of existing domestic dwellings through technocentric material interventions and, simultaneously identify demand-side factors that may be influencing the success (or lack thereof) of efforts towards reducing domestic energy consumption.
- Promising quantitative results, namely 23% and 12% drops on average in gas and electricity use after energy efficiency retrofitting, contrast with evidence of change-resistant domestic practices and possible rebound effects resulting from a shift in expectations concerning thermal comfort.
- The ECF is useful when trying to identify which households may be more open to initiatives to transform householders' energy practices such as advice on how to reduce domestic energy use, particularly those with high energy usage and indoor temperature, without having to live in uncomfortable conditions.

To conclude, the ECF is well suited to the investigation of household energy cultures, due to its focus on micro-level energy use and its exposure to systemic influences as well as its tripartite structure. The latter proved to be particularly useful in this study because it helped to distinguish between energy-cultural elements that are rather 'sticky' (i.e. resistant to change) and those that proved to be rather malleable. For example, certain space and water heating practices could be shown to 'survive' a rather dramatic change in material conditions (installation of new heating system as part of retrofit programme), leading to lower-than-expected energy savings. Questions remain whether the ECF can be fruitfully applied to study energy cultures at meso or macro levels (e.g. large businesses with a specific organisational energy culture, national energy cultures).

Regarding the operationalisation of the ECF, efforts to capture empirically the different elements of energy cultures posed considerable challenges in this study. This issue could re-emerge in future research that uses the ECF to frame secondary analyses of existing large-scale energy use data. Moreover, further longitudinal multi-method research on how energy cultures are driving the large variability of energy consumption and energy savings across households could help to formulate targeted building retrofit and environmental mitigation policy measures for different groups of buildings and people, thereby moving away from ‘one size fits all’ approaches.

Despite these limitations, the ECF helps to capture empirically how changes in one of the elements of energy culture – in this case altered material conditions brought about by an energy retrofitting programme – influence other elements of energy culture and the influence energy culture elements have on household energy consumption and the internal environment. Although the small sample size of this study cannot justify adopting a sociotechnical approach to retrofitting programmes, it adds to the growing calls for such an approach to be implemented for energy savings to be realised [337], [338]. If a culturally sensitive sociotechnical approach is applied on a national scale in retrofit projects, it could help to (i) strengthen the evidence for policy-makers in building retrofitting, (ii) inform future targeted building retrofit and environmental mitigation policy measures for different groups of buildings and people, including economically vulnerable parts of the population, (iii) develop hands-on change initiatives and demonstrator projects that seek to transform both householders’ attitudes, perceptions and social norms as well as their daily practices and (iv) draw attention to energy-cultural diversity to aid countries in meeting their energy efficiency and carbon reduction targets, including EU member states committed to implementing the EU’s Energy Union.

Chapter 6. How Effective is an Energy Efficiency Building Retrofit and Feedback on Energy Usage at Reducing Energy Consumption in Irish Social Housing?

6.1 Introduction

Changes in the material conditions of the case study houses from an energy efficiency retrofit resulted in changes of perceptions, space and water heating energy consumption habits and temperature profiles of the households as presented in Chapter 5. One household changed their water heating habits due to electricity demand feedback information from an IHD. While changes in material conditions were found to be effective in reducing the energy consumption in many of the monitored case study buildings (examined in Chapter 4 and Chapter 5), the households were also given energy consumption feedback as part of an energy saving initiative (ESI) to see if the feedback would elicit any changes in the householder energy demand practices and in turn the householders energy consumption. The ESI focused on four energy consumption end use areas: (i) space heating (SH) services, (ii) domestic hot water (DHW) heating services, (iii) domestic appliance services and (iv) cooking services; (i) and (ii) were provided primarily through gas energy consumption, while (iii) and (iv) were provided primarily through electricity energy consumption. The design, implementation and effectiveness of the ESI is presented in this chapter. In addition, the effectiveness of the energy efficiency building retrofit at reducing energy consumption is provided and compared to the effectiveness of the ESI for eliciting changes in the householder's energy consumption.

The parameters employed in Chapter 6 to examine the interrelationships between the operational energy demand practices in buildings, the people occupying buildings and the materials and technology used in the retrofit of the buildings are depicted in Figure 6.1.

Prof Henrike Rau from Ludwig Maximilian University of Munich and Dr Richard Manton from Engineers Ireland contributed to this section in choosing and designing the feedback format of the direct and indirect energy consumption feedback given to the householders.

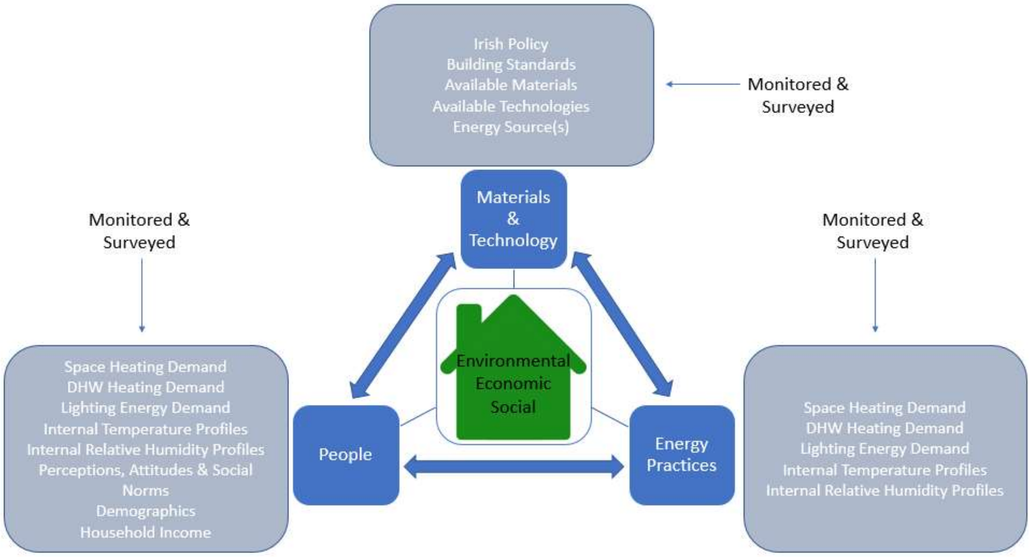


Figure 6.1: The parameters employed in Chapter 6 to examine how the interrelationships between the operational energy demand practices in buildings, the people occupying buildings and the materials and technology used in a building influence the environmental, economic and social impact of building retrofits.

6.2 Methodology

6.2.1 Data Collection

James & Ambrose [240] conducted a study comparing the effectiveness of energy efficiency retrofit measures and energy consumption feedback measures for reducing energy consumption. The James & Ambrose [240] study involved 320 low-income Australian households involved in an energy efficiency programme. The households were divided among four groups: (i) houses which received one or more of eleven different energy efficiency retrofit measures, (ii) houses which received one or more of five different behaviour change measures, (iii) houses which received both energy efficiency retrofit and behaviour change measures and (iv) a control group [240].

Gupta & Barnfield present the findings of a study on 63 households which received either technical energy efficiency retrofit measures and/or behavioural change measures [241]. As the physical building characteristics, technical retrofit measures and behavioural change measures varied amongst the sample of monitored houses, it was not possible to differentiate between the effectiveness of the technical retrofit measures and the behavioural change measures.

The ESI study on the effectiveness of energy consumption feedback differs from the James & Ambrose [240] and Gupta & Barnfield study [241] whereby the households received similar building energy efficiency retrofit measures, as discussed in Section 4.3.2, and the same energy consumption feedback, discussed later in Section 6.2.2 .

The analysis on the effectiveness of energy consumption feedback in comparison to an energy efficiency building retrofit is based on data collected during three monitoring phases: pre-retrofit, post-retrofit and the ESI. There were three main forms of data collection during the pre-retrofit and post-retrofit monitoring phases: (i) pre-retrofit and post-retrofit participant surveys, (ii) installation of internal environment and electricity consumption data-logging instrumentation and (iii) monthly readings of electricity and gas meters. Owl +USB [331] and Efergy E2 with USB [332] electricity meters acted as IHDs and electricity consumption data-logging instrumentation during phase one and phase two. As the houses have digital gas meters installed, no IHD or gas consumption data logging instrumentation could be installed without interrupting the gas supply. Therefore, no IHD or gas consumption data logging instrumentation to monitor the gas consumption profiles of the households were installed.

Optional feedback on the changes in the energy consumption and internal environment of their houses was offered to the householders following completion of post-retrofit monitoring. The householders were also offered the option of further information on how they could potentially reduce their energy consumption. As detailed energy consumption and internal environment data existed for 22 houses (one household withdrew from the study during phase two), only the households involved in the pre-retrofit and post-retrofit monitoring were asked if they wanted feedback on the changes in their energy consumption and internal environment following the energy efficiency retrofit. The same households were also asked if they wanted to become involved in the ESI.

19 of the households received feedback on the changes in energy consumption and internal environment following the energy efficiency retrofit, with 14 (out of the 19 households) choosing to become involved in the ESI. The remaining houses in the estate (excluding those involved in the pre- and post-retrofit monitoring) are used as a control group. There were three main forms of data collection used during the ESI study: (i) effectiveness of energy consumption feedback surveys, (ii) internal environment and electricity consumption data-logging instrumentation, and (iii) monthly readings of electricity and gas meters. A timeline of the three different monitoring phases is provided in Table 6.1.

Table 6.1: Phases of the data collection.

Phase No.	Phase of Project	Timeline
Phase one	Pre-Retrofit	February 2015-July 2015
Phase two	Post-Retrofit	October 2015-February 2017
Phase three	ESI	March 2017-January 2018

6.2.2 Energy Consumption Feedback Design

6.2.2.1 Energy Efficiency Retrofit Feedback Design

Lessons learned and recommendations from published literature were used when deciding the method and format of the feedback given to the householders on the changes in their energy consumption and internal environment following the energy efficiency retrofit. This work is based on several published literature reviews on providing direct and indirect feedback to energy consumers, including [229]–[233], [237], [243], [339]–[341]. Direct energy feedback is instantaneous information on the energy consumption of a building. This is often provided through an IHD, a webpage, plug meters, thermostats, manually reading meters or ambient devices [229]. Indirect feedback is processed information that is often provided through billing, e-mail, SMS, energy reports or webpages.

Indirect feedback is considered more suitable for demonstrating changes in energy consumption from energy efficiency retrofit measures [233]. Historical energy consumption feedback is considered to be effective for reducing energy consumption [231], [232], however, it is often provided in combination with other feedback strategies making it difficult to isolate its effectiveness [342]. Historic consumption was included as part of the energy efficiency retrofit indirect feedback as it allowed the householders to see the changes in their energy consumption and internal environment following the energy efficiency retrofit.

For the feedback reports on gas consumption and internal environment, the householders were provided with a monthly one-page report with comparable pre-retrofit and post-retrofit monthly periods. The one-page report detailed the average daily gas consumption, 24-hr temperature profiles and monthly temperature and relative humidity of the rooms with a data logger for comparable pre-retrofit and post-retrofit monthly periods. As gas consumption was related to the SH and DHW, monthly average external temperature, relative humidity, wind speed, solar intensity and total rainfall information collected from Dublin Airport [259] were also provided.

For the feedback reports on electricity consumption, householders were provided with a monthly one-page report showing their hourly, daily and monthly electricity consumption for comparable pre-retrofit and post-retrofit periods. Previous studies have found that detailed indirect information presented in terms of consumption and costs over time (daily, weekly, monthly) can result in savings ranging from 1.5-4% [230], [242], [342], [343]. The hourly, daily and monthly electricity consumption results were represented as vertical bar charts. Fischer [232] previously found that energy consumers prefer historical energy consumption to be represented as vertical bar charts.

Fischer [232] also found feedback on energy consumption to be more effective if it is presented in an understandable and appealing way that catches the consumer's attention. Furthermore, Vine et al. [231] recommended feedback to energy consumers to be presented plainly, engagingly, and tailored to the householder. Buchanan et al. [341] also highlighted comprehension issues by energy consumers in feedback strategies. Considering these recommendations and issues, any increase/decrease in gas and electricity energy consumption, and average house temperature was highlighted by a simple green (positive change) and red (negative change) arrow. In addition, boilers (gas) and light bulbs (electricity) representing the average kWh/day used during the month were also included.

Normative energy feedback allows for energy consumption comparison to other households [232]. The ESI would have been able to overcome typical problems with providing normative feedback that other studies have as energy consumption data was available for houses in a similar climate and having the same technical characteristics (building type, heating system etc.) [342]. However, providing normative feedback can be counterproductive [232], [341], may elicit social pressure and have a boomerang effect where high energy consuming homes decrease their energy consumption and low energy consuming homes increase their energy consumption [232], [344].

However, while designing the feedback format, the fact that the householders were living in social housing had to be considered carefully. This was especially prevalent when deciding whether to provide householders with normative feedback based on other houses in the estate as some of the householders' energy usage may be constrained by their income levels. Normative feedback had the potential for occupants to live in dangerously cold homes [341], feel guilty about not being able to afford to heat their houses or use appliances as often as other neighbours. In order to avoid this, normative feedback was not used in this work as part of the indirect feedback. Furthermore, the property managers overseeing the housing estate expressed concerns about individual households receiving information on the energy usage of other households as they believed it would lead to complaints from some householders on their personal energy usage levels.

Feedback, including changes in gas and electricity usage following the energy efficiency retrofit, was given to the householders on two separate visits. This was done to not overburden the householders with all the information at once.

6.2.2.2 ESI Feedback Design

Monthly indirect feedback reports were also part of the ESI feedback strategy as sustained energy consumption reduction requires indirect, frequent and accurate feedback reports [230], [233], [345]. The format of the feedback reports in the ESI study remained the same as the feedback reports given on the changes in energy consumption following the energy efficiency retrofit. This mitigated possible comprehension issues [341] with the householders involved in the study.

Since the houses had digital gas meters installed and no IHD could be installed without interrupting the gas supply, direct feedback on household gas consumption could not be provided. Monthly gas and internal environment reports were not provided during the ESI because there was no remote access (for the research team) to the gas consumption and internal environment profiles of the households.

Direct feedback was used for electricity consumption as it is considered to be effective for reducing electricity energy consumption [229]–[233]. IHDs are the most common method of providing direct feedback to energy consumers. Darby [233] suggested IHDs are most useful if they show instantaneous usage, expenditure and historic feedback as a minimum, and Vine et al. [231] recommended feedback to be both interactive and digital.

Based on these findings, direct feedback on whole house electricity consumption was provided to the householders using the Owl Intuition online web dashboard [346]. While there were Owl +USB [331] and Efergy E2 with USB [332] IHDs installed in the houses during pre-retrofit and post-retrofit monitoring phases, they were left out of sight of the householders and the householders were not taught by the researchers how to use the meters to examine the electricity demand of different appliances in the house. As both meters presented electricity consumption in different formats, it was decided to use the Owl online web dashboard [346] as the uniform direct electricity consumption feedback method during the ESI study.

The online dashboard was available to the householders by either installing an application on their mobile phone or logging into their account using a computer/laptop. The mobile phone, computer or laptop acted as the IHD. The online dashboard provided the user with instantaneous electricity consumption and costs while also allowing the user to view historical daily, weekly and monthly electricity consumption information in terms of either energy or cost. Electricity consumption data collected through the online dashboard was available to download and used to create monthly electricity consumption reports for the householders. Research has found the use of an IHD can help in generating energy savings but typically wanes over time [340], [345]. The use of an IHD is considered more effective when other strategies are also employed to engage energy consumers. These strategies include information/tips on energy efficiency measures, energy reduction goals or disaggregated appliance electricity consumption [230], [231], [233], [342], [345], [347].

Although previous research found energy saving tips to be ineffective [342], others have found social housing occupants to be interested in both general and tailored energy savings advice which complemented direct and indirect energy feedback [348]. Energy saving tips for SH, DHW, appliance usage and cooking were included as part of the monthly electricity reports. It was a conscious decision not to include energy reduction targets in the feedback to householders, as providing this information could result in people living in dangerously cold homes. While disaggregated electricity consumption has been recommended previously for energy feedback studies [231], [232], [347], Kelly and Knottenbelt [349] found its effectiveness to be only 1.5% higher against aggregate feedback. Despite being interested in providing disaggregated electricity feedback, the limited resources available to the researchers meant that only aggregated electricity consumption feedback was included in the ESI.

Face-to-face interaction between the energy consumer and feedback provider is considered important for trust and engagement in the feedback information [228], [342]. Furthermore, Delmas et al. [227] found that strategies involving individualised audits and consulting to be more effective for energy conservation than strategies that provide historical, peer comparison feedback. Considering these factors, the researchers visited the houses involved in the ESI and installed the Owl Intuition equipment [346]. A householder was shown how to log onto the dashboard using both a mobile phone and laptop, and how to use the online dashboard to check the electricity demand of an appliance. The household kettle was used as a demonstrator to show the householder how to use the online dashboard to check the electricity demand of an appliance. In addition, it was explained what information the occupants could learn about their electricity consumption, including overnight base loads, peak usage periods and days with highest electricity usage. Each of the energy savings tips for SH, DHW heating, appliance usage and cooking were explained to the householders, and how they could be implemented without compromising the health and comfort of the occupants. Following this interaction, monthly electricity reports including the energy saving tips were sent to the householders through either an e-mail or the postal service. An example of the one-page report given to a householder for feedback on their gas consumption, internal environment and electricity consumption in addition to an example of the energy savings tips for SH, DHW heating, appliance usage and cooking are shown in Appendix F. A sample of the effectiveness of energy consumption feedback survey is shown in Appendix G.

6.3 Results

The figures for gas and electricity energy usage presented correspond to secondary energy and do not account for losses across the network. Similar to the temperature data presented in Chapter 4, all available non-erroneous comparable temperature data from each of the houses is presented in this section. This is due to this section not using the temperature data to explain the differences in energy consumption across the various case studies but rather to see if the individual households experienced an increase or decrease in household temperature.

6.3.1 Gas Consumption and Internal Environment Feedback

The gas usage and internal environment feedback reports that show changes following the energy efficiency retrofit were given to the householders at the end of February 2017. Energy savings tips for SH and DHW heating were explained to the householders, as well as the advice on how the energy savings could be implemented without compromising the health and comfort of the householders. The main SH system installed in the houses incorporated a domestic gas boiler with radiators supplying heat to each of the rooms. A solid fuel open fire, multi-fuel stove, gas fire or electric fire act as a secondary heating system in the living room, but were rarely used by the householders receiving feedback. Following the retrofit, as discussed in

Chapter 4, the main SH gas boiler was upgraded to a more energy efficient gas boiler. SH system controls were installed to control two heating zones. The downstairs zonal temperature was controlled using a Climote HUB [350] installed in the hallway. The digital user interface allowed the householders to set the SH setpoint temperature and SH operation schedule. The upstairs zonal temperature was controlled using TRVs installed on all the radiators.

DHW was provided mainly through the gas boiler. The gas boiler heated the water which was stored in a hot water cylinder. The householders also had the option of using an electric immersion to heat the water. Following the retrofit, a more energy efficient hot water cylinder was installed. The setpoint temperature of the DHW was controlled by a thermostat located at the base of the hot water cylinder. DHW heating schedules could be programmed using the Climote HUB [350].

The gas usage information/tips given to the householders recommended SH and DHW setpoints and methods on how to reduce gas usage, such as manually varying TRV settings based on weather, reducing water consumption when showering or using extra blankets/clothes instead of switching on heating. Following the advice, 10 householders requested the researchers reduce their SH temperature setpoint settings. Householders did not want the SH temperature setpoint too low because they found the room temperature profiles were not uniform. To warm the coldest room up to a satisfactory level, in some cases, the setpoint needed to be high to ensure the controls did not switch off the boiler too early. Other studies have also highlighted the poor control of heating systems in houses effecting how they are operated [204], [351] leading to householders overriding thermostat settings due to non-uniform temperature of rooms in house [351]. Some householders also stated that the heating system installers recommended having the SH temperature setpoint at a high level and to operate the SH manually, essentially removing the added functionality of the thermostat.

Some of the householders found the DHW to be scalding coming out of water taps since the new gas boiler system was installed. The householders believed it was due to the new boiler being more efficient compared to the old gas boilers. Upon review of the DHW settings, it was discovered that eight (out of 14) of the hot water tanks had their thermostat settings set to 85°C or higher. None of the householders had adjusted the thermostat on the tank to be that high meaning the heating system installers must have set the thermostat levels. The householders were recommended to set the DHW setpoint between 60-65°C. The eight householders requested their thermostats to be adjusted down to 60°C based on the information given. One household adjusted their DHW setpoint up by 10°C to 60°C based on the information given.

At the end of March 2017, the researchers returned to the 14 households to review how effective the householders found the gas saving tips, provide feedback on the changes in their electricity consumption following the energy efficiency retrofit and begin the electricity consumption feedback element of the ESI. None of the householders had implemented the methods on how to reduce gas usage, such as manually varying TRV settings based on weather, reducing water consumption when showering or using extra blankets/clothes instead of switching on heating. However, all the households had kept their DHW thermostat settings the same, following the advice, whereas five (of the 10) households who reduced their SH thermostat setpoints had increased the settings. The householders who readjusted their SH thermostat settings found that they needed to have the setpoint setting high for all rooms to achieve a satisfactory temperature level. The householders who reduced their SH temperature setpoints could not tell if it helped reduce their gas usage. The householders who reduced their DHW temperature setpoints were very happy as the water was no longer scalding coming out of water taps, with some feeling their gas consumption had reduced. Upon collecting all the equipment at the end of the study a year later, four of the eight households that reduced their DHW thermostat setpoints had changed the setpoints again. Two increased the settings by 10°C. One household increased the temperature back up to 90°C while one household reduced their settings down to 30°C. The household that reduced the temperature to 30°C noted that they did not have hot water for three weeks and thought it was a problem with the boiler. They believed one of the children may have turned it down by accident. It was turned back to 60°C upon this discovery. Table 6.2 details how the householders operated their SH and DHW heating and the heating thermostat setpoints before the advice (A), after the advice (B), day of the feedback survey (C) and at the end of the study (D).

Table 6.2: The SH and DHW settings of the households involved in the feedback study.

		SH Setpoint (°C)					DHW Setpoint (°C)			
Case	SH OS	A	B	C	D	DHW OS	A	B	C	D
1	MN	30	25	25	30	MN	60	60	60	60
2	PR/MN	23	23	23	20	PR/MN	50	60	60	60
3	PR/MN	25	22	24	23	PR/MN	90	60	60	60
4	MN	30	22	30	30	MN	90	60	60	60
5	MN	28	22	22	25	MN	85	60	60	60
6	PR/MN	20	20	20	20	PR/MN	65	65	65	65
8	PR	20	20	20	20	PR	60	60	60	60
10	PR/MN	25	22	22	25	PR/MN	90	60	60	70
11	PR/MN	28	22	28	25	PR/MN	85	60	60	60
13	MN	28	21	22	24	MN	60	60	60	60
14	PR/MN	30	23	23	23	PR/MN	90	60	60	90
17	MN	30	23	23	27	MN	90	60	60	30
20	PR/MN	26	26	26	24	PR/MN	65	65	65	65
22	MN	30	22	25	25	PR/MN	90	60	60	70

Abbreviation

A: Before Advice
B: After Advice
C: Day of Feedback Questionnaire
D: End of Study
MN: Manual Operation
OS: Operational Settings
PR: Schedule and Thermostat
PR/MN: Schedule and Thermostat and Manual Operation

6.3.1.1 Gas Consumption and Internal Environment Changes following Energy Efficiency Retrofit and ESI

In order to examine how the energy efficiency building retrofit and ESI impacted the SH and DHW gas consumption, the gas consumption during heating and non-heating months for comparable periods across the pre-retrofit, post-retrofit and ESI phases of the study was examined. The gas consumption during each heating period is based on gas meter data collected on the dates detailed in Table 6.3. The gas consumption data during the heating season was normalised using the HDDs experienced at Dublin Airport during the dates in Table 6.3, assuming a base temperature of 15.5°C. The normalised gas usage data (kWh/HDD) for each phase was multiplied by the average HDD experienced at Dublin Airport from 25th February to the 29th May for 10 years starting from 2005. An average daily gas usage for each phase was then calculated. As HDDs are used for normalising SH energy, the non-heating season data was not normalised using HDDs.

Table 6.3: Heating and non-heating periods with comparable gas consumption data across the pre-retrofit, post retrofit and ESI phases of the study.

Phase	Meter Collection Dates	Heating Period
Pre-Retrofit	25th Feb 2015-29th May 2015	Heating Season
	30th May 2015-22nd July 2015	Non-Heating Season
Post-Retrofit	13th Feb 2016-27th May 2016	Heating Season
	27th May 2016-21st July 2016	Non-Heating Season
ESI	25th Feb 2017-1st June 2017	Heating Season
	2nd June 2017-3rd Aug 2017	Non-Heating Season

Heating Season

The average daily heating season gas usage for different groupings of houses across the three phases is given in Table 6.4. Unequal variance t-tests were conducted to examine what groupings experienced statistically significant differences (95% confidence level) in their average daily gas consumption following the energy efficiency retrofit and ESI. The houses constructed in 2000 experienced, on average, a statistically significant reduction (-7.6 ± 5.7 kWh/day) in gas consumption in 2016 following the retrofit works. However, the houses constructed in 1994 did not experience, on average, a statistically significant reduction in gas consumption in 2016 following the retrofit (-5.0 ± 5.0 kWh/day). The houses in the estate experienced, on average, a reduction in gas consumption (-6.3 ± 3.7 kWh/day) in 2016 following the retrofit works. This gas reduction occurred despite gas energy prices falling in 2016 compared to 2015 in Ireland [249]. In addition, the average external temperature during the heating season of the pre-retrofit period (Table 6.3) was 7.8°C. This dropped by 0.6°C to 7.2°C during the post-retrofit heating season period.

Gas prices in Ireland continued to fall during 2017 when the ESI study was conducted [249]. The houses in the estate, on average, increased their gas consumption in 2017 compared to 2016 although not significantly. This occurred despite the average external temperature during the heating season ESI period (Table 6.3) being 9.5°C. This was an increase of 2.3°C compared to the post-retrofit heating season period. The average house gas reduction experienced by the estate in 2016 was halved during 2017. Both the houses in the ESI study and the control group of the ESI study increased, on average, their gas consumption although insignificantly.

There was a change in the number of people living in four houses involved in the feedback study. A single parent in Case 5 had their son move back into the house during 2017. Despite this, the household gas consumption decreased in 2017. Case 1 had friends staying for 3 months during 2016. Despite this, the gas consumption of Case 1 increased in 2017 compared to 2016. Case 17 reduced its gas consumption during 2017 despite the child and two grandchildren of the single mother moving back into the house. The gas consumption of Case 22 decreased following one of their children moving out. A change in the number of people living in the households does not appear to be primary factor for the change in gas consumption. Also, for electricity consumption, a change in the number of people living in the five households does not appear to be primary factor for the change in electricity consumption. As shown in Chapter 5, a household's energy consumption can be influenced by several factors. As such, the results of all 14 households involved in the ESI are used when assessing the impact of the ESI. Following the ESI, relative to the control group, the households receiving feedback experienced a statistically insignificant average reduction of 1.2 ± 2.7 kWh/day during the heating season.

Table 6.4: Change in gas usage (kWh/day) of houses during the heating season following the retrofit works and ESI.

	Gas Usage			Difference in Gas Usage (95% CI)		
Group (n=sample size)	PRE	POST	ESI	POST-PRE	ESI-POST	ESI-PRE
All Houses (n=56)	26.8	20.5	23.8	-6.3 ± 3.7*	3.2 ± 3.3	-3.0 ± 4.0
1994 Houses (n=29)	26.0	21.0	23.0	-5.0 ± 5.0	2.0 ± 4.5	-3.2 ± 5.5
2000 Houses (n=27)	27.6	20.0	24.6	-7.6 ± 5.7*	4.5 ± 5.0	-3.0 ± 6.2
Houses in ESI Study (n=14)	29.5	23.6	26.1	-5.9 ± 6.7	2.5 ± 6.0	-3.5 ± 7.4
Control Group (n=33)	24.4	18.2	21.3	-6.1 ± 4.9*	3.7 ± 4.5	-2.5 ± 5.4
Study Group Relative to Control Group					-1.2 ± 2.7	

Abbreviations

ESI: Energy Saving Initiative	POST: Post-Retrofit
PRE: Pre-Retrofit	*statistically significant

The changes in gas consumption and temperature profiles during the heating season across the three phases of the study for the households involved in the ESI are given in Table 6.5. Despite the internal environment data logging instrumentation being installed by researchers during the data collection periods, there remained missing and erroneous data recorded by the data logging instrumentation.

Internal environment data for individual rooms for a number of houses were missing for data analysis. The amount of missing data varied from case to case. Reasons for the missing data included (i) loss of the data logging instrumentation by the householder, (ii) loss of battery power in the data logging instrumentation, (iii) full capacity of the data logger's internal memory, (iv) malfunction of data logging instrumentation, (v) data loggers moved by a householder and (vi) data loggers in direct sunlight.

All the temperature data collected from the data loggers were plotted for visual inspection to identify any errors or anomalies. Reasons identified for exclusion of data included (i) data logger moved near heat source or window and (ii) temperature profile of room significantly different to other rooms of house with no logical explanation.

Comparable temperature data available for rooms during the heating periods of each phase of the study was used for analysis. A two-sample z-test for comparing two means was used for examining whether houses experienced a statistically significant change (95% confidence level) in average house temperature profiles.

Following the energy efficiency retrofit works, all but two of the households involved in the feedback study experienced a reduction in gas consumption (Table 6.5). The two households which experienced an increase in gas consumption had two of the three highest temperature increases post-retrofit and had two of the three lowest pre-retrofit average temperatures. Eight households experienced a temperature increase following the retrofit works with seven being a statistically significant increase. The four households that experienced a temperature decrease had four of the five highest gas consumptions pre-retrofit.

Overall following the energy efficiency retrofit, two of the households appeared to value increased comfort levels over savings (increased gas consumption and increased average temperature), seven experienced both gas savings and improved comfort levels (reduced gas consumption and increased average temperature), while four sacrificed some comfort while also saving energy (reduced gas consumption and reduced average temperature).

Table 6.5: Change in gas usage (kWh/day) and indoor temperature profile (°C) of households involved in the ESI during the heating season.

	Gas Usage				Average House Temperature					Space Heating Settings				
Case	PRE	POST-PRE	ESI-POST	ESI-PRE	PRE	POST-PRE	ESI-POST	ESI-PRE	Temperature of Room(s)	OS	A	B	C	D
$1^{1, 2, 3}$	19.6	-5.8	2.8	-3.0	18.8	0.4 ± 0.5	1.2 ± 0.5*	1.6 ± 0.5*	FBR	MN	30	25	25	30
2	27.3	-4.2	2.6	-1.7	19.9	0.4 ± 0.3*	0.9 ± 0.3*	1.3 ± 0.3*	KT, LR, FBR, BBR, Box	PR/MN	23	23	23	20
$3^{2, 4}$	31.1	-7.3	6.4	-0.9	19.8	0.6 ± 0.4*	1.2 ± 0.4*	1.8 ± 0.3*	KT, FBR	PR/MN	25	22	24	23
4^{3}	32.3	-7.5	2.1	-5.3	20.6	-1.4 ± 0.5*	1.3 ± 0.4*	-0.1 ± 0.5	KT, LR, FBR, Box	MN	30	22	30	30
$5^{1, 4}$	25.4	-4.2	-5.7	-9.9	18.3	0.8 ± 0.5*	0.1 ± 0.5	0.9 ± 0.5*	KT, LR, FBR	MN	28	22	22	25
6^{1}	29.2	-1.0	3.1	2.1	18.7	1.7 ± 0.3*	0.0 ± 0.3	1.7 ± 0.3*	LR, FBR, BBR	PR/MN	20	20	20	20
8^{4}	36.1	-15.3	-0.1	-15.4	20.0	-0.7 ± 0.3*	0.5 ± 0.4*	-0.2 ± 0.4	KT, LR, FBR, BBR	PR	20	20	20	20
10^{3}	44.3	-12.4	2.6	-9.7	21.8	-0.0 ± 0.3	0.2 ± 0.3	0.1 ± 0.3	KT, LR, FBR, BBR, Box	PR/MN	25	22	22	25
$11^{2, 4}$	49.5	-13.4	9.6	-3.8	20.6	-0.2 ± 0.3	1.9 ± 0.4*	1.7 ± 0.4*	LR	PR/MN	28	22	28	25
$13^{3, 4}$	21.9	-2.1	0.3	-1.8	18.5	1.0 ± 0.3*	0.7 ± 0.3*	1.8 ± 0.3*	KT, LR, Box	MN	28	21	22	24
$14^{2, 3, 4}$	19.6	-1.5	4.6	3.0	18.1	1.5 ± 0.4*	1.8 ± 0.4*	3.3 ± 0.4*	LR, BBR, Box	PR/MN	30	23	23	23
$17^{1, 2, 4}$	11.5	2.5	-0.4	2.0	16.7	2.0 ± 0.4*	1.8 ± 0.4*	3.9 ± 0.4*	KT, LR, BBR	MN	30	23	23	27
20^{4}	39.1	-12.9	4.6	-8.3	20.1	N/A	N/A	2.0 ± 0.3*	KT, LR, BBR	PR/MN	26	26	26	24
$22^{1, 2, 3, 4}$	26.7	2.2	2.0	4.2	18.2	1.6 ± 0.4*	0.4 ± 0.4*	2.0 ± 0.3*	KT, LR, Box	MN	30	22	25	25

Abbreviations

A: Before Advice
B: After Advice
BBR: Back Bedroom
Box: Box Bedroom
C: Day of Feedback Questionnaire
D: End of Study
ESI: Energy Saving Initiative
FBR: Front Bedroom
KT: Kitchen
LR: Living Room
PR: Schedule and Thermostat

MN: Manual Operation
OS: Operational Settings
PR/MN: Schedule and Thermostat and Manual Operation
PRE: Pre-Retrofit
POST: Post-Retrofit

[1] Households with change in number of people living in house

[2] Households who use pre-pay meter for gas

[3] Households who stopped using electrical immersion to heat DHW

[4] Member of household receiving government welfare

*statistically significant

While only two of the households appeared to value an increased comfort level over savings following the retrofit in 2016, eight of the households appeared to value an increased comfort level over further savings in 2017. While the 2.3°C increase in average external temperature during 2017 compared to 2016 may have contributed to many of the households increasing their internal temperatures, only three of the households reduced their gas consumption in 2017 despite the external temperature increase.

Reducing the SH temperature setpoints was generally not effective at reducing gas consumption. Seven of the households that reduced their SH setpoints experienced a temperature increase, with five of the seven increasing their gas consumption. How the householders operated their heating system appeared to have more of an influence on their gas consumption during the heating season. The four lowest gas users during 2017 operated their heating system manually, whereas the four highest gas users operated their heating system with a schedule and manually if not satisfied with comfort levels.

Non-Heating Season

The average daily non-heating season gas usage for different groupings of houses across the three phases is given in Table 6.6. Neither all the houses in the estate (-1.3 ± 2.5 kWh/day), the houses constructed in 1994 (0.9 ± 2.3 kWh/day) nor the houses constructed in 2000 (-3.6 ± 4.4 kWh/day) reduced their daily gas consumption significantly in 2016 following the retrofit works. This was unexpected considering the main water heating system was improved by installing a more energy efficient gas boiler and insulated hot water cylinder in each of the houses in the estate. In addition, June of 2015 was unusually cold and may have required some SH use by the householders. By not correcting the gas usage using HDDs, the gas usage in 2016 should be theoretically lower than in 2015. Following the ESI study in 2017, relative to the control group, the households receiving feedback experienced a non-statistically significant decrease in gas consumption compared to 2016 (-1.2 ± 1.6 kWh/day).

The change in gas consumption and temperature profiles during the non-heating season across the three phases of the study for the households involved in the feedback study is given in Table 6.7. Six of the 14 households experienced an increase in their gas consumption during the non-heating months following the retrofit works. Four of the six households that increased their gas consumption reported to have stopped using their electrical immersion for DHW in conjunction with their gas boiler. All four households experienced the highest increases in gas consumption following the retrofit. Two households that had their DHW setpoint at 90°C increased their gas consumption.

Table 6.6: Change in gas usage (kWh/day) of houses during the non-heating season following the retrofit works and ESI.

	Gas Usage			Difference in Gas Usage (95% CI)		
Group (n=sample size)	PRE	POST	ESI	POST-PRE	ESI-POST	ESI-PRE
All Houses (n=55)	8.9	7.7	8.1	-1.3 ± 2.5	0.4 ± 1.8	-0.8 ± 2.4
1994 Houses (n=29)	6.3	7.1	7.9	0.9 ± 2.3	0.7 ± 2.0	1.6 ± 2.3
2000 Houses (n=26)	11.8	8.2	8.2	-3.6 ± 4.4	0.1 ± 3.2	-3.4 ± 4.2
Houses in ESI Study (n=14)	8.3	8.2	8.0	-0.1 ± 3.2	-0.2 ± 3.1	-0.3 ± 3.3
Control Group (n=32)	8.3	6.8	7.8	-1.5 ± 3.7	1.0 ± 2.7	-0.5 ± 3.6
Study Group Relative to Control Group					-1.2 ± 1.6	
Abbreviations						
ESI: Energy Saving Initiative				POST: Post-Retrofit		
PRE: Pre-Retrofit				*statistically significant		

Unlike the SH, changing the setpoint temperature of the DHW thermostats appeared to have an impact on the gas consumption of the houses. Seven of the 10 households that experienced a gas reduction during 2017 reduced their DHW temperature setpoint. For the householders who saved gas energy after reducing their DHW thermostat setpoints, the savings ranged from 0.1 kWh/day to 5.4 kWh/day. For two of the four households that reduced their gas consumption by less than 1 kWh/day, they had an electric shower installed. Two of the households that relied on a power shower had savings of greater the 2.1 kWh/day (Case 10 and Case 22). However, in Case 22, one of the children in the house moved out.

Two of the other seven households that reduced their DHW temperature setpoints and reduced their gas consumption experienced a change in the number of people living in the house. For Case 5, the child of the single parent living in the house moved back in. A child and two grandchildren of a single mother living in Case 17 moved back into the house.

21 houses in the estate experienced an increase in gas usage following the retrofit with 33 experiencing a decrease. Eight of the 14 households in the feedback study had the thermostat on their hot water cylinder set at a very high temperature and six of the 14 households reported to have stopped using their electrical immersion for DHW in conjunction with their gas boiler. Thus, it was possible that more households in the estate that were not involved in the feedback study, had their DHW setpoints at an incorrect level and stopped using their electrical immersion. This may partly explain why the estate, on average, did not experience a statistically significant reduction in gas consumption following the retrofit works in the non-heating season.

Another possible explanation was the change in controls and functionality of the new heating system. Using the old heating system controls, the householders could operate the SH and DHW heating system simultaneously. With the new heating system, householders could not operate the SH and DHW heating systems simultaneously. If both the SH and DHW heating systems are operated simultaneously, the DHW takes precedence over the SH. If the householders have schedules set up for their DHW needs and the setpoints are set at a high temperature, the boiler system may operate for the full schedule if the water temperature setpoint is not reached.

If operated manually, the SH and DHW heating controls for the old heating system would require the controller to switch the system on/off. Using the new system controls, the householders use the boost buttons located at the base of the heating system control panel in the hallway to operate the system manually (See Figure 4.8). The boost button turns on either the SH or DHW heating for a default time which can be set at half hour intervals. Depending on how diligently the householders operated the old heating system may impact how effective the new controls are. If the householders manually operate the DHW using the boost button and the DHW setpoint is set to a high temperature, the boiler system may operate for the full default time setting if the water temperature setpoint is not reached.

6.3.1.2 Gas Consumption and Internal Environment Changes Following ESI

Only six months of comparable data was available across the pre-retrofit, post-retrofit and ESI phases of the study, to investigate how the retrofit works and ESI impacted

Table 6.7: Change in gas usage (kWh/day) and indoor temperature profile (°C) of households involved in the ESI during the non-heating season.

	Gas Usage (kWh/day)				Average House Temperature (°C)					DHW Heating Settings				
Case	PRE	POST-PRE	ESI-POST	ESI-PRE	PRE	POST-PRE	ESI-POST	ESI-PRE	Temperature of Room(s)	OS	A	B	C	D
1[1, 2, 3]	4.0	6.2	-0.4	5.8	22.0	1.5 ± 0.4*	-0.2 ± 0.3	1.4 ± 0.3*	FBR, Box	MN	60	60	60	60
2	9.2	0.1	2.9	2.9	22.1	0.9 ± 0.4*	0.3 ± 0.3	1.2 ± 0.3*	KT, LR, FBR, BBR, Box	PR/MN	50	60	60	60
3[2, 4]	4.9	-0.4	-0.5	-0.9	21.5	1.3 ± 0.3*	-0.2 ± 0.3	1.1 ± 0.3*	KT, FBR	PR/MN	90	60	60	60
4[3]	5.7	3.0	-0.4	2.6	21.9	0.3 ± 0.4	0.1 ± 0.3	0.4 ± 0.3*	KT, LR, FBR, Box	MN	90	60	60	60
5[1, 4]	9.9	-4.7	-0.9	-5.6	21.1	0.8 ± 0.4*	-0.4 ± 0.4	0.4 ± 0.4*	KT, LR, FBR	MN	85	60	60	60
6[1]	4.0	1.2	1.9	3.1	21.7	0.8 ± 0.3*	-0.3 ± 0.3	0.4 ± 0.3*	LR, BBR	PR/MN	65	65	65	65
8[4]	9.3	-2.4	-0.1	-2.5	20.9	1.0 ± 0.4*	-0.1 ± 0.4	0.9 ± 0.4*	KT, LR, FBR, BBR, Box	PR	60	60	60	60
10[3]	14.7	-0.7	-5.4	-6.1	22.8	0.7 ± 0.3*	-0.6 ± 0.3*	0.1 ± 0.3	KT, LR, FBR, BBR	PR/MN	90	60	60	70
11[2, 4]	16.5	-1.6	2.5	0.9	21.9	1.0 ± 0.4*	0.2 ± 0.5	1.2 ± 0.4*	LR	PR/MN	85	60	60	60
13[3, 4]	2.1	2.1	-1.8	0.3	20.6	1.4 ± 0.4*	0.4 ± 0.4	1.8 ± 0.4*	KT, LR, Box	MN	60	60	60	60
14[2, 3, 4]	10.4	-1.3	2.1	0.8	21.7	1.2 ± 0.4*	1.0 ± 0.3*	2.3 ± 0.4*	LR, BBR, Box	PR/MN	90	60	60	90
17[1, 2, 4]	6.5	-4.7	-0.5	-5.2	20.8	1.5 ± 0.4*	0.4 ± 0.3*	1.9 ± 0.4*	KT, LR, FBR, BBR	MN	90	60	60	30
20[4]	13.4	-4.4	-0.3	-4.8	21.1	2.0 ± 0.3*	0.3 ± 0.3*	2.3 ± 0.3*	KT, LR, BBR	PR/MN	65	65	65	65
22[1, 2, 3, 4]	6.0	6.0	-2.1	3.9	20.3	1.8 ± 0.4*	-0.6 ± 0.3*	1.2 ± 0.3*	KT, LR, BBR, Box	PR/MN	90	60	60	70

Abbreviations

A: Before Advice
B: After Advice
BBR: Back Bedroom
Box: Box Bedroom
C: Day of Feedback Questionnaire
D: End of Study
ESI: Energy Saving Initiative
FBR: Front Bedroom
KT: Kitchen
LR: Living Room
PR: Schedule and Thermostat
MN: Manual Operation
OS: Operational Settings
PR/MN: Schedule and Thermostat and Manual Operation
PRE: Pre-Retrofit
POST: Post-Retrofit

[1] Households with change in number of people living in house
[2] Households who use pre-pay meter for gas
[3] Households who stopped using electrical immersion to heat DHW
[4] Member of household receiving government welfare
*statistically significant

the SH and DHW gas consumption. 10 months of comparable data was available for the post-retrofit and ESI study (Table 6.8).

The gas consumption data during the heating season was normalised using the HDDs experienced during the dates in Table 6.8 assuming a base temperature of 15.5°C. The normalised gas usage data (kWh/HDD) for each phase was multiplied by the average HDD experienced at Dublin Airport from the 13th February to the 27th May and the 23rd September to the 24th February for 10 years starting from 2005. For the non-heating season of 2017, the month of September was not considered as it was an unusually cold month which may have resulted in more SH consumption.

Table 6.8: Heating and non-heating periods with comparable gas consumption data across the post-retrofit and ESI phases of the study.

Phase	Meter Collection Dates	Heating Period
Post-Retrofit	13th Feb 2016-27th May 2016 & 23rd Sept 2016-24th Feb 2017	Heating Season
	28th May 2016-22nd Sept 2016	Non-Heating Season
ESI	25th Feb 2017-1st June 2017 & 5th Oct 2017-10th Jan 2018	Heating Season
	2nd June 2017-1st Sep 2017	Non-Heating Season

Heating Season

Unequal variance t-tests and two-sample z-test for comparing difference in means were used on the gas and temperature data for examining any statistical differences. Gas usage across the estate during the heating season of 2017 when the ESI study was on-going experienced a non-statistically significant increase (Table 6.9). Relative to the control group, the gas consumption of the houses involved in the ESI remained unchanged on average (0.0 ± 1.9 kWh/day). Only three households involved in the feedback reduced their gas consumption. Three of the lowest gas users operated their heating system manually, whereas the top three highest gas users operated their heating system using a combination of a schedule and manually if not satisfied with comfort levels.

Overall following the feedback, seven of the households appeared to value an increased comfort level over energy savings, with three of the seven households significantly increasing their temperature profile. One household experienced gas savings and improved comfort levels, while two households sacrificed some comfort for saving energy. The results did not suggest reducing the SH setpoints reduced the gas consumption of houses. The way the householders operated their heating system appeared to have more of an influence on their gas consumption during the heating season (Table 6.11).

Table 6.9: Change in gas usage (kWh/day) of houses during the heating season following the ESI.

	Gas Usage		Difference in Gas Usage (95% CI)
	POST	ESI	ESI-POST
All Houses (n=55)	25.2	26.7	1.5 ± 3.5
1994 Houses (n=28)	25.5	26.3	0.8 ± 5.1
2000 Houses (n=27)	24.9	27.1	2.2 ± 5.0
Houses in ESI Study (n=14)	28.8	30.3	1.5 ± 6.4
Control Group (n=32)	22.3	23.9	1.5 ± 4.5
Study Group Relative to Control Group			0.0 ± 1.9
Abbreviations			
ESI: Energy Saving Initiative		POST: Post-Retrofit	
PRE: Pre-Retrofit		*statistically significant	

Non-Heating Season

The average daily non-heating season gas usage for different groupings of houses during 2016 and 2017 is given in Table 6.10. The estate's gas consumption during the non-heating season of 2017 increased compared to 2016 insignificantly (0.7 ± 1.7 kWh/day). While the gas consumption of the houses receiving feedback increased during 2017, their consumption relative to the control group decreased insignificantly (-0.7 ± 1.4 kWh/day).

Table 6.10: Change in gas usage (kWh/day) of houses during the non-heating season following the ESI.

	Gas Usage		Difference in Gas Usage (95% CI)
	POST	ESI	ESI-POST
All Houses (n=58)	7.2	7.9	0.7 ± 1.7
1994 Houses (n=30)	6.3	7.4	1.1 ± 2.0
2000 Houses (n=28)	8.1	8.4	0.3 ± 2.9
Houses in ESI Study (n=14)	7.7	8.2	0.4 ± 3.2
Control Group (n=34)	6.4	7.6	1.2 ± 2.5
Study Group Relative to Control Group			-0.7 ± 1.4
Abbreviations			
ESI: Energy Saving Initiative		POST: Post-Retrofit	
PRE: Pre-Retrofit		*statistically significant	

Table 6.11: Change in gas usage (kWh/day) and temperature profile (°C) of households involved in the ESI during the heating season.

	Gas Usage (kWh/day)		Average House Temperature (°C)			Space Heating Settings				
Case	POST	ESI-POST	POST	ESI-POST	Temperature of Room(s)	OS	A	B	C	D
1[1, 2, 3]	17.3	-0.7	18.5	0.7 ± 0.6*	KT, BBR, Box	MN	30	25	25	30
2	26.5	4.9	20.6	0.6 ± 0.3*	KT, FBR, BBR, Box	PR/MN	23	23	23	20
3[2, 4]	29.9	1.6	20.6	0.2 ± 0.4	KT, FBR	PR/MN	25	22	24	23
4[3]	29.3	6.5	19.6	1.3 ± 0.4*	KT, LR	MN	30	22	30	30
5[1, 4]	24.1	-1.6	19.0	-0.1 ± 0.5	KT, LR, FBR	MN	28	22	22	25
6[1]	36.2	0.9	N/A	N/A	N/A	PR/MN	20	20	20	20
8[4]	28.3	-3.4	20.0	-0.6 ± 0.4*	KT, LR, FBR, BBR, Box	PR	20	20	20	20
10[3]	38.5	1.0	21.8	-0.5 ± 0.4*	KT, LR, Box	PR/MN	25	22	22	25
11[2, 4]	44.7	2.8	N/A	N/A	N/A	PR/MN	28	22	28	25
13[3, 4]	25.6	0.1	19.9	0 ± 0.3	KT, LR, Box	MN	28	21	22	24
14[2, 3, 4]	22.6	4.2	19.9	0.9 ± 0.4*	LR, BBR, Box	PR/MN	30	23	23	23
17[1, 2, 4]	15.8	1.6	19.5	0.4 ± 0.4	KT, LR, Box	MN	30	23	23	27
20[4]	30.9	3.0	N/A	N/A	N/A	PR/MN	26	26	26	24
22[1, 2, 3, 4]	33.4	0.7	20.0	0.3 ± 0.4	KT, Box	MN	30	22	25	25

Abbreviations

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FBR: Front Bedroom
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LR: Living Room
PR: Schedule and Thermostat

MN: Manual Operation
OS: Operational Settings
PR/MN: Schedule and Thermostat and Manual Operation
PRE: Pre-Retrofit
POST: Post-Retrofit

[1] Households with change in number of people living in house

[2] Households who use pre-pay meter for gas

[3] Households who stopped using electrical immersion to heat DHW

[4] Member of household receiving government welfare

*statistically significant

Table 6.12: Change in gas usage (kWh/day) and temperature profile (°C) of households involved in ESI during the non-heating season.

	Gas Usage (kWh/day)		Average House Temperature (°C)			DHW Settings				
Case	POST	ESI-POST	POST	ESI-POST	Temperature of Room(s)	OS	A	B	C	D
1[1, 2, 3]	8.0	2.0	23.3	-0.0 ± 0.3	FBR, Box	MN	60	60	60	60
2	8.7	3.6	23.0	0.4 ± 0.3*	KT, FBR, BBR, Box	PR/MN	50	60	60	60
3[2, 4]	4.8	-0.9	22.7	-0.3 ± 0.3*	KT, FBR	PR/MN	90	60	60	60
4[3]	8.8	-0.5	22.0	0.1 ± 0.3	KT, LR, FBR, Box	MN	90	60	60	60
5[1, 4]	5.0	-0.7	21.9	-0.4 ± 0.4*	KT, LR, BBR	MN	85	60	60	60
6[1]	5.0	1.2				PR/MN	65	65	65	65
8[4]	6.5	-0.2	21.9	-0.4 ± 0.3*	KT, LR, FBR, BBR, Box	PR	60	60	60	60
10[3]	11.3	-2.5	23.1	-0.5 ± 0.3*	KT, LR, BBR, Box	PR/MN	90	60	60	70
11[2, 4]	14.9	4.1	22.9		LR	PR/MN	85	60	60	60
13[3, 4]	3.9	-1.4	22.2	-0.1 ± 0.3	KT, LR, Box	MN	60	60	60	60
14[2, 3, 4]	9.0	2.5	23.0	0.8 ± 0.3*	LR, BBR, Box	PR/MN	90	60	60	90
17[1, 2, 4]	1.6	-0.0	22.4	0.1 ± 0.3	KT, LR, FBR, BBR, Box	MN	90	60	60	30
20[4]	8.3	0.4	23.1	0.2 ± 0.3	KT, LR, BBR	PR/MN	65	65	65	65
22[1, 2, 3, 4]	12.3	-1.8	22.1	-0.3 ± 0.3*	KT, BBR, Box	PR/MN	90	60	60	70

Abbreviations

A: Before Advice
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ESI: Energy Saving Initiative
FBR: Front Bedroom
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PR: Schedule and Thermostat

MN: Manual Operation
OS: Operational Settings
PR/MN: Schedule and Thermostat and Manual Operation
PRE: Pre-Retrofit
POST: Post-Retrofit

[1] Households with change in number of people living in house

[2] Households who use pre-pay meter for gas

[3] Households who stopped using electrical immersion to heat DHW

[4] Member of household receiving government welfare

*statistically significant

Eight of the 14 households that received feedback reduced their gas consumption (Table 6.12). Seven of the eight households that reduced their gas consumption, also adjusted their DHW temperature setpoints to a lower setting. One household that increased their DHW temperature setpoint following advice, increased their gas consumption. While changing the SH setpoint setting did not appear to effect gas consumption, the households that reduced their gas consumption and DHW temperature setpoint settings, saved on average 0.3 kWh/day.

6.3.1.3 Rent and Retrofit Cost Payback Periods

Assuming all the houses in the estate had the same gas price tariffs as reported by SEAI [249] in 2015, 2016 and 2017, the average annual spend on gas excluding VAT was €545 in 2015, €404 in 2016 and €432 in 2017, respectively. As discussed in Chapter 4 and Chapter 5, the households in the estate experienced a rent increase for five years to pay for the retrofit works in combination with a grant received from SEAI. The payback periods for the rent increase for the retrofit works are shown in Figure 6.2. The payback periods for the total cost of the retrofit works f are shown in Figure 6.3. The payback periods shown are based on the post-retrofit gas of 2016 and 2017 relative to 2015 pre-retrofit gas consumption. Future operational energy costs and rent increases are discounted with a 4% discount rate. Future gas and electricity prices are also used. Electricity and gas fuel costs are assumed to increase with annual average growth rate of 3.0% and 2.7%, respectively, as assumed in the Chapter 4 analysis. The electricity payback periods are discussed later in Section 6.3.2.3.

52% of the households will have paid back their rent increase within 10 years based on their 2016 gas consumption (Figure 6.2). 20% of the households increasing their energy consumption in 2016 relative to 2015 resulted in them having no payback. 7% of the householders will have paid back their rent increase consumption within 10-20 years.

Based on the 2017 gas consumption, the number of households that will pay back their rent increase within 10 years decreased by 18% to 34% (Figure 6.2). This results in a 5% increase in the number of households having no payback and a 14% increase in the number of households having a payback period within 10-20 years. Based on the previous findings of this chapter, the decrease in Irish gas consumption prices may have resulted in many of the households in the estate heating their houses to a higher internal temperature resulting in an increased gas energy consumption.

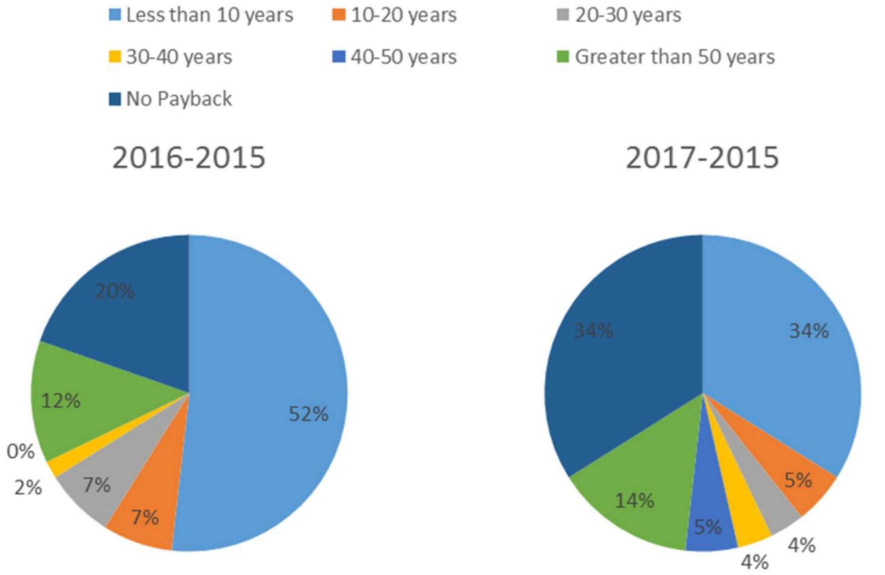

Figure 6.2: Payback periods for the households in the estate for their rent increase based on their gas usage savings of 2016 and 2017 relative to 2015.

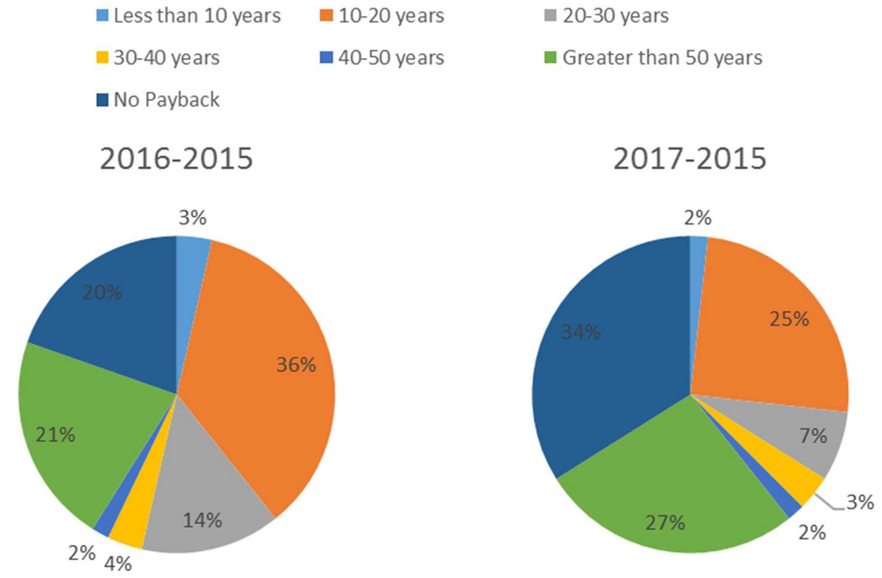

Figure 6.3: Payback periods for the households in the estate for the total retrofit cost based on their gas usage savings of 2016 and 2017 relative to 2015.

The majority of households will not pay back the total cost of the retrofit within 10 years based on the 2016 and 2017 gas consumption. 36% of the households will pay back the retrofit cost within 10 to 20 years. 21% of the households will have a payback period of more than 50 years.

Based on the 2017 gas energy consumption, the number of households with a payback period ranging from 10 to 20 years dropped by 9% to 25%. This 9% decrease resulted in more households with no payback period and a payback period of more than 50 years.

For the feedback given to the householders in the ESI study, based on the energy consumption, temperature data and the interviews with the householders, it was found that the only advice that was effective at reducing gas consumption was changing the DHW thermostat setting. Assuming (i) the non-heating season gas usage in the households was related to the DHW heating services, (ii) the average daily non-heating season gas usage was the same DHW daily gas usage throughout the year, (iii) changes in gas usage in 2016 were related to the energy efficiency retrofit works and (iv) changes in gas usage in 2017 were related to the ESI study, the control group of the ESI study saved €52 in DHW heating in 2016 from the energy efficiency retrofit and increased their DHW heating demand by €11 in 2017. The eight households that reduced their DHW thermostat setting, saved €26 from the energy efficiency retrofit in 2016 and a further €29 from changing their DHW thermostat setting in 2017.

6.3.2 Electricity Consumption Feedback

Households involved in the electricity feedback started receiving their direct and indirect feedback by the end of March 2017. The electricity consumption feedback given to the householders was found to be ineffective in most of the case studies. Several reasons identified for its ineffectiveness, based on discussions with the householders, are discussed as follows.

Engaging people to use IHDs has been previously found to be difficult [339]–[341], and it was similar in this study. Despite installing the online web dashboard for 14 households and demonstrating what could be learned from using it, only five households reported logging onto the online dashboard with only two using the tool to examine the electricity consumption of various appliances. One of the two households that examined the consumption of electricity appliances using the online dashboard found it difficult to understand the information provided, which has also been shown to be an issue with direct feedback [341], [351], [352]. This occurred despite an explanation from the researchers when the online dashboard was first installed. Data comprehension depends on the manner of presentation and the design of the display interface [353]. However, the researchers designing the ESI feedback format were limited by not being able to design an online display interface of their own and relying on the existing OWL interface.

Motivation has been identified as an essential factor for behaviour change [354] and was also highlighted by many householders as to why they had not changed their electricity consumption. Householders of Case 5, 8, 10 and 13 were not motivated to reduce their electricity consumption as they believed they were not heavy electricity users and they only used appliances when they were needed. These householders said that they were not going to keep track of how long or how often they used specific appliances. If they needed to use appliances, they would use them. They did not mind if their electricity consumption increased or decreased slightly from month to month, as they would rationalise the change as needing to use appliances for specific reasons or during a particular time of the year. The feedback had not encouraged them to change, as termed in other research, the natural rhythm of their consumption [339].

While acknowledging the interesting information provided in the electricity consumption reports, the householders of Case 20 noted their lack of motivation to change their electricity consumption stemmed from their children. Both their children have special needs and use many appliances in their usual routines. The parents did not want to change their children’s routines. Hargreaves et al. (2010) also found that medical conditions of householders can dictate how energy is used by a household.

While the parents of Case 20 did not want to encourage their children to change their electricity consumption practices, others in the ESI study had difficulty engaging members of the household to be conservative with electricity usage. Other research studies have also identified this issue [339], [340]. A parent in Case 3 did not believe either the direct or indirect feedback encouraged her to reduce her electricity consumption. She believed herself to be efficient when it came to using electricity but finds herself in an ‘on-going challenge’ with her children regarding this issue. There may be some truth to her theory. She was away from the house for part of June and July in 2017 while on holidays. Despite only her daughter being in the house, the electricity consumption of the house increased by 15% in June and 5% in July compared to 2016. Case 3 also had higher electricity in both June and July in 2017 compared to April and May 2017 when the parent was present in the home.

Parents in Case 2, 5, 11, 17 and 22 also highlighted the role their children played during the electricity feedback. A single mother in Case 11 did not use the online dashboard, read any of the monthly electricity reports or implement any of the electricity saving tips provided during the study. She said that she did not have any time to read any of the information or try and change the electricity consumption of the household because of her three young children. She explained that the household can ‘be crazy’ with barely a minute to herself meaning trying to reduce electricity consumption is a hard thing to do. A parent in Case 17 noted that her child and two grandchildren moved back into the house in October 2016 resulting in increased electricity consumption. Whereas parents in Case 22 had one of their children move out during 2017 and the household reduced its electricity consumption. Householders of Case 17 and 22 implemented some of the tips provided to them but, with the change in number of people living in the house, it was not possible to determine whether it had any effect on their electricity consumption. The single parent of Case 5 had his son move back in during 2017, although it did not impact the electricity consumption significantly compared to 2016.

The electricity consumption feedback was useful for the parents living in Case 2, as the parents used the feedback to teach their children about electricity consumption. Case 2 used the direct feedback to help highlight to their children how much electricity the house appliances use to help reduce the electricity consumption. The parents in this house noted their children had a ‘big impact’ on the overall electricity consumption, with eight children typically being in the house at weekends. This household also tried to reduce their showering time and limit the use of the tumble dryer, based on the information/tips given. However, the parents noted the difficulty with this at times. Despite trying to reduce their electricity usage, the results of this household showed an increase in total electricity consumption in 2017. The householders noted they were out of the house for periods during April, June and July of 2016 which may have caused the increase in 2017. For each of the other months, i.e. March, May and August to December, their electricity usage during 2017 reduced compared to 2016.

A householder in Case 6 only started reading the monthly detailed electricity reports from October 2017 onwards, as she claimed to have been too busy before that with organising her wedding. She said after seeing how much electricity the household used overnight, she started plugging appliances out before going to bed. However, it was difficult to assess if this had a significant impact on her electricity consumption, as she plugged out the router for the online web dashboard resulting in lost data. Based on the electricity meter readings, electricity consumption for October 2017 reduced compared to the October 2016. However, electricity consumption for November and December in 2017 was similar to November and December in 2016.

Case 4 experienced the second largest reduction in electricity consumption of the households in the ESI study in 2016 compared to 2015. The householders believed this was due to them having stopped using their electrical shower and electrical immersion to heat their water for domestic use. They changed these behaviours because one of the householders used the Efergy E2 meter [332] installed to check the electricity demand of their electrical shower and electrical immersion, despite not being shown by the researchers how to use the Efergy E2 meter [332]. After seeing the large demand of both the electrical shower and electrical immersion, they removed their electrical shower, stopped using their electrical immersion in conjunction with the gas boiler for hot water and relied solely on their gas boiler for water heating following the retrofit works.

Case 22 experienced the largest reduction in electricity consumption of the households in the ESI study in 2016 compared to 2015. The householders of Case 22 believed this was due to a combination of them installing an electricity pre-pay meter, removing the use of the electrical immersion in conjunction with the gas boiler for hot water and one of the children living in the house moving out.

A parent living in the house of Case 14 believed herself to be energy efficient and put her energy efficiency down to her pre-pay meter. She said it allowed for 'easier monitoring' of her electricity consumption. Pre-payment systems have also been previously found to be effective in reducing electricity consumption [235], [237]. Six of the 14 cases used pre-payment for their electricity consumption.

6.3.2.1 Electricity Consumption Changes Following Energy Efficiency Retrofit and ESI

Four months of electricity consumption data was available for cross comparison across the three phases of the study (Table 6.13). The electricity consumption pre-retrofit was from the 1st April 2015 to the 22nd July 2015, post-retrofit was from the 31st March 2016 to the 21st July 2016 and the ESI was from the 23rd March 2017 to the 3rd August 2017. However, electricity consumption data for all the houses in the estate was not available due to lack of access to meters, incorrectly recorded meter readings and inability to read meters of houses with digital electricity meters.

The housing estate insignificantly reduced its electricity consumption during 2016 (-1.4 ± 1.5 kWh/day), following the retrofit works of 2015. This was opposite to that reported by SEAI who reported an annual increase in energy consumption in the Irish residential sector since 2014 [43]. This reduction in electricity consumption across the estate occurred despite electricity prices in Ireland reducing in 2016, compared to 2015. Electricity prices reduced further in 2017, but no significant change between the electricity consumption of 2016 and 2017 occurred in the estate (0.0 ± 1.5 kWh/day).

Table 6.13: Change in electricity usage (kWh/day) of houses following the retrofit works and ESI.

	Electricity Usage			Difference in Electricity Usage (95% CI)		
	PRE	POST	ESI	POST-PRE	ESI-POST	ESI-PRE
All Houses (n=43)	11.2	9.8	9.8	-1.4 ± 1.5	0.0 ± 1.5	-1.4 ± 1.5
1994 Houses (n=21)	11.6	9.3	9.6	-2.2 ± 2.3	0.3 ± 2.2	-1.9 ± 2.2
2000 Houses (n=22)	10.9	10.3	10.0	-0.6 ± 2.0	-0.4 ± 2.1	-0.9 ± 2.1
Houses in ESI Study (n=13)	11.3	9.4	9.7	-1.9 ± 2.3	0.3 ± 2.0	-1.6 ± 2.4
Control Group (n=23)	10.7	9.4	9.3	-1.3 ± 2.3	-0.1 ± 2.4	-1.4 ± 2.3
Study Group Relative to Control Group					0.4 ± 1.2	

Abbreviations

ESI: Energy Saving Initiative	POST: Post-Retrofit
PRE: Pre-Retrofit	*statistically significant

The ineffectiveness of the electricity consumption feedback, typically found while questioning the householders on how effective/useful they found the electricity consumption feedback, is represented in the electricity consumption data of the households in Table 6.13. Relative to the control group, the consumption of the houses receiving feedback increased insignificantly (0.4 ± 1.2 kWh/day).

Table 6.14 shows the change in electricity consumption of households involved in ESI following retrofit works and ESI. 10 of the 14 households reduced their electricity consumption in 2016 compared to 2015.

Table 6.14: Change in electricity consumption (kWh/day) of households involved in the ESI following the retrofit works and ESI.

	Electricity Usage			Difference in Electricity Usage		
Case	PRE	POST	ESI	POST-PRE	ESI-POST	ESI-PRE
1[1, 2, 3]	12.7	8.3	10.1	-4.3	1.7	-2.6
2	12.4	11.2	11.8	-1.1	0.6	-0.6
3[2, 4]	10.8	8.8	9.1	-1.9	0.2	-1.7
4[3]	15.8	7.9	8.9	-7.8	0.9	-6.9
5[1, 4]	7.1	8.3	7.7	1.1	-0.6	0.6
6[1]		10.5	10.8		0.2	
8[4]	6.6	6.6	7.6	0.0	1.0	1.0
10[3]	15.9	11.6	11.9	-4.3	0.3	-4.0
11[2, 4]	9.6	8.3	8.8	-1.3	0.5	-0.8
13[3, 4]	9.8	8.4	8.6	-1.5	0.2	-1.3
14[2, 3, 4]	8.9	7.7	7.9	-1.2	0.2	-1.0
17[1, 2, 4]	8.8	9.3	10.7	0.4	1.4	1.8
20[4]	16.9	15.7	16.3	-1.2	0.7	-0.6
22[1, 2, 3, 4]	11.5	10.0	6.5	-1.5	-3.6	-5.1

Abbreviations

PRE: Pre-Retrofit
POST: Post-Retrofit
ESI: Energy Saving Initiative

[1] Households with change in number of people living in house removed

[2] Households who use pre-pay meter for gas

[3] Households who stopped using electrical immersion to heat DHW

[4] Member of household receiving government welfare

*statistically significant

Six of the 10 household that reduced their electricity consumption in 2016, reported to have stopped using their electric immersion to heat their water and had the largest reductions in electricity consumption. 32 houses in the estate reduced their electricity consumption in 2016, compared to 2015, and 11 increased their electricity consumption. 12 of the 32 houses that reduced their electricity consumption reduced their electricity consumption by more than 2 kWh/day, and six of these 12 houses had increases in their gas consumption during the non-heating season. This suggested that other households in the estate may have stopped using their electrical immersion to heat their hot water, contributing to the significant reduction in electricity usage by the housing estate during 2016 compared to 2015.

Part of the electricity consumption reduction experienced by households may also be explained by each household receiving a set of energy efficient lightbulbs to install in their homes as part of the retrofit. However, based on the households that were surveyed, changing the existing lights to the new energy efficient lightbulbs was not as effective as may have been envisioned. Some households already had low energy lightbulbs installed in their homes, some had lightbulb connections that did not suit the new low energy lightbulbs while others preferred the illuminance that other, more energy demanding, lightbulbs gave off. In 2017 while the households were receiving their electricity consumption feedback, only two households reduced their electricity consumption. 23 of the houses in the estate increased their electricity consumption in 2017, compared to 2016, with no overall statistically significant change.

6.3.2.2 Electricity Consumption Changes Following ESI

10 months of comparable electricity consumption data was available for the post-retrofit and ESI study (Table 6.15). The electricity consumption for post-retrofit was from the 31st March 2016 to the 24th February 2016 and ESI was from the 23rd March 2017 to the 10th January 2017. The electricity consumption feedback proved to be ineffective. The houses receiving feedback increased their consumption by 0.9 ± 0.7 kWh/day relative to the control group.

Table 6.15: Change in electricity usage (kWh/day) of houses following the ESI.

	Electricity Usage		Difference in Electricity Usage (95% CI)	
	POST	ESI	ESI-POST	ESI-PRE
All Houses (n=46)	10.9	10.2	-0.6 ± 1.4	-1.3 ± 1.4
1994 Houses (n=22)	10.5	10.0	-0.5 ± 2.0	-1.5 ± 2.0
2000 Houses (n=24)	11.2	10.5	-0.7 ± 2.1	-1.2 ± 2.2
Houses in ESI Study (n=13)	10.1	10.1	-0.1 ± 2.0	-1.1 ± 2.2
Control Group (n=25)	9.9	9.1	-1.0 ± 2.2	-1.6 ± 2.2
Study Group Relative to Control Group			0.9 ± 0.7*	
Abbreviations				
ESI: Energy Saving Initiative PRE: Pre-Retrofit			ESI: Energy Saving Initiative *statistically significant	

6.3.2.3 Rent and Retrofit Cost Payback Periods

Assuming all the houses in the estate had the same electricity price tariffs as reported by SEAI [249] in 2015, 2016 and 2017, the average annual spend on electricity was €940 in 2015, €800 in 2016 and €772 in 2017, respectively. As highlighted in earlier sections, householders reported to have stopped using their electric immersion for meeting the DHW needs while gas and electricity energy usage data for other houses in the estate suggested other households in the estate followed suit. Additionally, each household was given a set of low energy lightbulbs.

Table 6.16: Change in electricity consumption (kWh/day) of households involved in ESI following ESI.

	Electricity Usage			Difference in Electricity Usage		
Case	PRE	POST	ESI	POST-PRE	ESI-POST	ESI-PRE
1[1, 2, 3]	10.9	8.5	9.2	-2.4	0.6	-1.8
2	12.9	12.4	12.5	-0.5	0.12	-0.3
3[2, 4]	11.9	9.6	9.5	-2.3	-0.1	-2.4
4[3]	13.2	9.6	9.0	-3.6	-0.6	-4.2
5[1, 4]	7.0	8.6	8.6	1.6	-0.0	1.6
6[1]		11.3	11.1		-0.3	
8[4]	6.9	7.2	8.0	0.4	0.8	1.1
10[3]	14.3	12.6	12.7	-1.7	0.1	-1.6
11[2, 4]	10.1	9.6	9.5	-0.6	-0.1	-0.6
13[3, 4]	9.4	9.1	9.7	-0.3	0.6	0.2
14[2, 3, 4]	9.3	8.0	8.1	-1.3	0.1	-1.2
17[1, 2, 4]	9.5	11.2	10.9	1.8	-0.3	1.4
20[4]	16.8	16.0	16.4	-0.8	0.4	-0.5
22[1, 2, 3, 4]	13.1	9.2	6.9	-3.9	-2.4	-6.2

Abbreviations

PRE: Pre-Retrofit
POST: Post-Retrofit
ESI: Energy Saving Initiative
[1] Households with change in number of people living in house removed
[2] Households who use pre-pay meter for gas
[3] Households who stopped using electrical immersion to heat DHW
[4] Member of household receiving government welfare
*statistically significant

Assuming the changes in electricity consumption in 2016 and 2017 relative to 2015 were due to the energy efficiency retrofit works, the payback periods for the household rent increase are shown in Figure 6.4. The payback periods for total cost of the retrofit works are shown in Figure 6.5.

The households reduced their annual electricity bill in 2016 relative to 2015, on average, by €140 despite a decrease in electricity prices [249]. For the rent increase, 29% of the households will have paid back their rent increase within 10 years based on their 2016 electricity consumption.

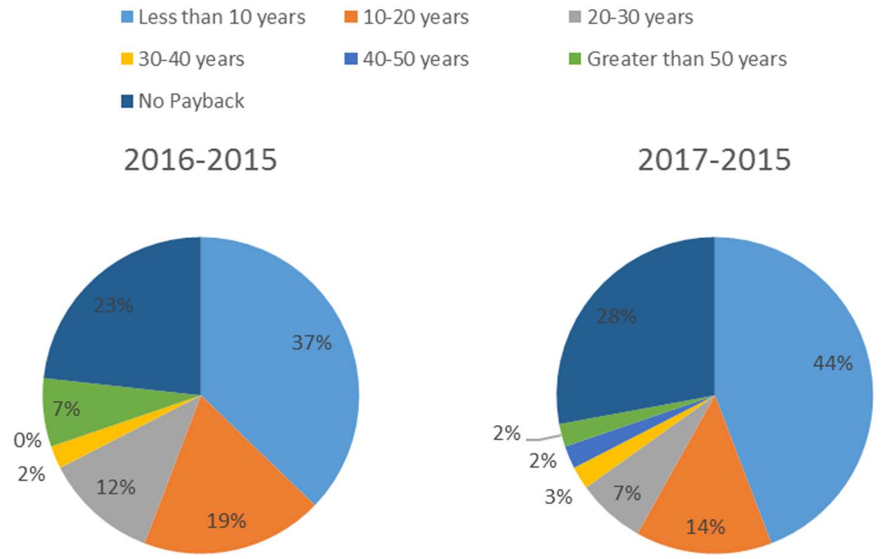

Figure 6.4: Payback periods for the households in the estate for their rent increase based on their electricity usage in 2016 and 2017 relative to 2015.

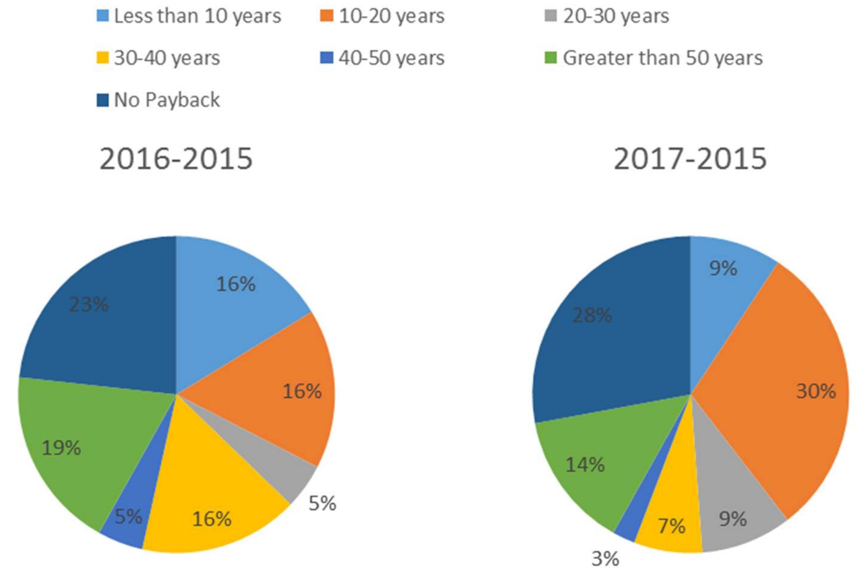

Figure 6.5: Payback periods for the households in the estate for the total retrofit cost based on their gas usage in 2016 and 2017 relative to 2015.

Based on the 2017 electricity consumption, the number of households that will have paid back their rent increase within 10 years increased by 5% to 34%. The households reduced their annual electricity bill in 2017 relative to 2015, on average, by €168. This was €28 more than in 2016 due to another decrease in electricity prices in 2017 [249].

Based on the electricity usage data and discussion with the householders, the ESI study was not effective at eliciting changes in the householder's electricity usage based on the electricity consumption feedback and energy saving tips they received. For the householders that stated they implemented some of the electricity saving tips, the electricity data was inconclusive on their effectiveness. Therefore, the investment of €54 for each electricity usage data logger installed for the ESI study was ineffective. During the post-retrofit monitoring phase in 2016, the householders of Case 4 stopped using the electric immersion and electric shower within their house due to the electric demand information they learned from their Efergy IHD. Based on their 2016 electricity savings, they had paid back the cost of the Efergy IHD within 2 months.

6.3.3 Effectiveness of Energy Efficiency Retrofit Relative to ESI for Energy Savings

A summary of the change in energy consumption by the housing estate following the retrofit works and the houses involved in the ESI, is given in Table 6.17 **Error! Reference source not found.**. The energy efficiency retrofit measures focused primarily on the thermal fabric and gas heating system of the houses. The housing estate reduced its gas consumption significantly (-6.3 ± 3.7 kWh/day) during the heating season of 2016 following the retrofit and reduced its electricity consumption insignificantly, (-1.0 ± 1.6 kWh/day) in 2016 during the heating season.

Electricity was the only one of the energy sources to experience a statistically significant reduction during the non-heating system. During the non-heating season, the housing estate reduced its gas consumption insignificantly (-1.3 ± 2.5 kWh/day) in 2016 following the retrofit and reduced its electricity consumption significantly (-1.8 ± 1.5 kWh/day) in 2016.

One of the aims of the study was to assess the difference in energy savings that could be achieved by providing energy consumption feedback to householders in comparison to an energy efficiency retrofit. Assuming any change in energy consumption was directly related to either the energy efficiency retrofit or the ESI study, the energy efficiency retrofit was more effective at reducing gas consumption during the heating season. The energy efficiency retrofit (-5.9 ± 6.7 kWh/day) and ESI (-1.2 ± 2.7 kWh/day) were statistically insignificant at reducing gas consumption in the 14 households involved in the ESI study during the heating season. The gas consumption of the households involved in the ESI increased on average during the non-heating season. However relative to the control group, these households reduced their gas consumption. During the non-heating season, the ESI (-1.3 ± 1.7 kWh/day) was more effective at reducing gas consumption compared to the energy efficiency retrofit (0.1 ± 3.2 kWh/day).

Table 6.17: Summary of the change in energy consumption by the estate from the retrofit works and the houses involved in the ESI.

			Comparable data for 3 phases		Comparable data for post-retrofit and ESI phases
Fuel Type	Heating Period	Retrofit[1]	Retrofit[2]	ESI [2, 3]	ESI[2, 3]
Gas (kWh/day)	Heating Season	-6.3 ± 3.7*	-5.9 ± 6.7	-1.2 ± 2.7	-0.1 ± 1.9
	Non-Heating Season	-1.3 ± 2.5	0.1 ± 3.2	-1.3 ± 1.7	-0.7 ± 1.4
Electricity (kWh/day)	Heating Season	-1.0 ± 1.6	-1.5 ± 2.4	1.2 ± 1.6	0.4 ± 1.2
	Non-Heating Season	-1.8 ± 1.5*	-2.3 ± 2.5	0.3 ± 1.1	0.9 ± 0.7*
Abbreviations					
ESI: Energy Saving Initiative PRE: Pre-Retrofit POST: Post-Retrofit [1]Estate			[2]Households in ESI [3]Relative to control group *statistically significant		

For electricity, the energy efficiency retrofit was more effective at reducing energy consumption compared to the ESI in both the heating season and non-heating season. Relative to the control group, the ESI increased the electricity consumption of the households involved in the ESI.

The average annual gas and electricity energy cost savings in the estate in 2016 following the retrofit in 2015 were €141 and €140, respectively. For the households involved in the ESI study, they saved, on average, €18 in gas energy over the course of a year in 2017. The electricity feedback was for the most part ineffective. Thus, in the context of this study, retrofitting technology was more effective at eliciting changes in energy consumption compared to energy saving feedback information.

6.4 Discussion and Conclusions

6.4.1 Effectiveness of Energy Efficiency Retrofit and ESI for Energy Savings

A group of households underwent two interventions. The first intervention primarily focused on installing energy efficiency retrofit technology to improve the thermal fabric and heating system of the houses. Assuming changes in energy consumption between 2015 and 2016 were directly related to the energy efficiency retrofit, the average annual gas and electricity energy cost savings in the estate in 2016 following the retrofit in 2015 were €141 and €140, respectively.

The second intervention was an ESI. The main purpose of the ESI implemented in this study was to provide householders with the ability to change their energy consumption, by providing them with skills and knowledge on how to reduce their energy consumption without compromising the health and comfort of the building occupants.

The ESI was implemented in a group of 14 households by providing direct and indirect feedback on electricity consumption using an interactive online web dashboard, a demonstration on how to use the online dashboard and detailed monthly electricity consumption reports. Appliance usage and cooking services energy saving information/tips were included as part of the monthly electricity reports. Energy savings information/tips for SH and DHW heating were provided as part of the gas consumption and internal environment feedback reports following the energy efficiency retrofit.

The most effective feedback was advising householders on the correct DHW temperature setpoint (as the temperature setpoints were set very high in some houses). This type of feedback could be characterised as non-time consuming as the householders only had to make one adjustment to their DHW thermostat settings. Any tips/information given to the householders on how to reduce gas and electricity consumption that involved investing time and continuous engagement were mostly unsuccessful. Assuming changes in energy consumption between 2016 and 2017 were directly related to the ESI, the households involved in the ESI study saved, on average, €18 in gas energy over the course of a year in 2017.

However, assuming the changes in energy consumption are directly related to either the energy efficiency retrofit or the ESI is a broad assumption given the limitations in the study design. For assessing the changes in energy consumption following the retrofit, ideally energy consumption data for a group of houses which did not receive an energy efficiency retrofit would act as a control group. However, this was not feasible. Furthermore, ideally the sample size of houses would have been larger in addition to more in-depth disaggregation of house energy consumption and temperature profiles to draw statistically robust conclusions from the data. Nevertheless, a combination of interview data with the householders, the energy usage data and IAQ data revealed interesting findings.

6.4.2 Challenges with Energy Efficiency Retrofit Technology

Many householders faced problems with the functionality of the new gas boiler SH and DHW heating system and its control system. The new heating system controller in the monitored case studies allowed the householders to program SH and DHW heating schedules. In addition, heating system controls were installed to control two heating zones. The downstairs controller allowed the householders to set a temperature set point to control the room temperature of the ground floor. The upstairs room temperatures were controlled using TRVs installed on each of the radiators. This is a common retrofit heating system controls package installed in houses in Ireland. In the monitored case studies, installing more functionality for heating system controls did not work as effectively as assumed in theory.

The change in controls and functionality of the new heating system meant the householders could not operate the SH and DHW heating systems simultaneously. If both the SH and DHW heating systems are operated simultaneously, the DHW takes precedence over the SH. While it was not possible to examine whether this change in functionality resulted in an increase in energy usage, many householders were not happy with the change in functionality. Many householders set the thermostat at a high temperature level. This essentially removed the added functionality of using the thermostat in the hallway to control the temperature of the house and when the boiler switched on/off. The TRVs in the upstairs rooms were commonly left at the same setting constantly. Better zoning controls should be installed for houses with large differences in temperature profiles across rooms to allow householders to properly control and automate their heating system. Many of the householders justified having a high temperature setpoint as they stated they were advised to operate the heating system using this method by the installers or the temperature profile across the rooms of the house was not uniform. Any advice given to householders by a stakeholder involved in the design or installation of a building retrofit, on how to operate their heating system, needs to be correct to ensure any new habits formed/locked in by householders are not inefficient energy demand practices.

Furthermore, educating heating system installation technicians may be as important as providing energy consumption feedback to householders. Some of the householders operated their SH system based on the advice they were given by the heating system installation technicians. In addition, the DHW thermostat setpoints which the technicians most likely set, remained in place for over a year despite being set at 90°C in some instances. The households that reduced their DHW thermostat and reduced their gas consumption during the non-heating season, saved on average 1.6 kWh/day. While the installed retrofit technology still achieved cost savings on average, the poorly commissioned heating system is estimated to have cost eight households, on average, €29 over the course of a year.

Thus improving handover and commissioning procedures for new heating systems and their controls in residential buildings is required, as suggested by other retrofit studies [204], [355]. A review of current practices for handover and commissioning protocol procedures by heating system installers in building retrofits is required to assess whether new protocol procedures need to be introduced. Additionally, property managers overseeing residential housing should be required to conduct assessments of heating system settings within the properties they oversee. This could help householders make significant savings, with one of the households in the ESI study estimated to have saved €149 over the course of a year from the DHW thermostat setting advice given to them by the researchers.

6.4.3 Challenges with Energy Consumption Feedback Study

The energy usage feedback study encountered several challenges in both the effectiveness of the feedback and verification of the changes in energy consumption. Several householders highlighted reasons for the ineffectiveness of the direct and indirect electricity feedback which have been found in other studies. Reasons included lack of engagement with the IHD, lack of motivation to reduce electricity consumption behaviours, comprehension issues with information provided, struggling to engage others in household to be more energy conservative and an electricity pre-pay meter having already minimised electricity consumption.

The electricity feedback was not completely ineffective. One household found the direct and indirect feedback useful for teaching their children about the electricity consumption of appliances. Another household started plugging out their appliances at night due to the information on the detailed monthly electricity report. Another household implemented some of the tips/information given to them to reduce electricity consumption. However, for the householders that stated they implemented some of the electricity saving tips, the electricity data was inconclusive on whether these households achieved long term energy savings.

Savings highlighted by the reports given to the householders before the start of the ESI may have reduced occupants' motivation to reduce their electricity consumption further. Occupants of Case 4 and 22 noted how the energy savings they achieved according to the retrofit impact energy reports given to them prior to the ESI, resulted in them not being as motivated to reduce their energy consumption further. If the advice was given to the householders at the time of the retrofit works, perhaps greater energy savings could have been achieved. However, given the small sample of houses in the study, it was required to split phases two (post-retrofit) and three (ESI) to assess whether the energy efficiency retrofit or ESI had a larger effect on the energy consumption and internal environment.

The timing of providing feedback may also have been an issue in this study. Maréchal [191] discussed how a "window" could be opened to break energy consumers' habits by implementing energy-efficiency measures (i.e. retrofitting a building) in combination with energy consumption-feedback and awareness campaigns. The householders received their first feedback reports over a year and a half after the retrofit works were completed. By potentially missing the "window" to break energy consumers' habits following the retrofit may have resulted in householders forming bad habits with the new heating system that were unbreakable a year and a half later. Five of the 10 households that reduced their SH thermostat setpoints had increased the settings again within a month of being given the advice. The possibility of becoming accustomed to higher indoor temperatures following the energy efficiency retrofit may have resulted in the householders unwilling to revert to a cooler environment.

The study identified reasons for changes in energy consumption practices following the energy efficiency retrofit including the functionality of the new heating system, incorrectly set DHW temperature setpoints, householders not using the electrical immersion anymore, removal of an electric shower, installation of a pre-pay meter, changes in household occupancy, desire for a higher thermal comfort and changes in fuel prices. Controlling and monitoring changes in these variables would come at a high expense in terms of both the cost of equipment and the time burden put on householders. Given the limited resources available to the researchers, controlling and monitoring these variables in the study was not feasible. However, further studies are needed to assess how these factors may contribute to the deficits often experienced in energy savings from energy efficiency retrofits estimated by engineering models.

In summary, this research found that:

- Assuming changes in energy consumption between 2015 and 2016 were directly related to the energy efficiency retrofit, the retrofit was statistically significant at reducing the gas consumption during the heating season (-6.3 ± 3.8 kWh/day) and electricity consumption (-1.8 ± 1.5 kWh/day) during the non-heating season.
- A combination of the functionality of the new heating system, incorrectly set DHW temperature setpoints and householders not using the electrical immersion anymore were identified as possible reasons as to why the estate did not experience a statistically significant reduction in gas consumption during the non-heating months.
- Assuming any change in energy consumption was directly related to either the energy efficiency retrofit or the ESI study, the energy efficiency retrofit was more effective at reducing gas consumption during the heating season. The energy efficiency retrofit (-5.9 ± 6.7 kWh/day) and ESI (-1.1 ± 2.7 kWh/day) were statistically insignificant at reducing gas consumption in the 14 households involved in the ESI study during the heating season. During the non-heating season, the ESI (-1.2 ± 1.6 kWh/day) was more effective at

reducing gas consumption compared to the energy efficiency retrofit (0.1 ± 3.2 kWh/day).

- The most effective feedback was to advise householders on the correct DHW temperature setpoint (as the temperature setpoints were very set high in some houses). This type of feedback could be characterised as non-time consuming as the householders only had to make one adjustment to their DHW thermostat settings. Any tips/information given to the householders on how to reduce gas and electricity consumption that involved investing time and continuous engagement were mostly unsuccessful.
- Issues with the commissioning and handover of the heating system in the monitored houses highlighted the need for a review of current practices for handover and commissioning by heating system installers in building retrofits to identify mandatory protocol procedures for commissioning and handover.
- Educating heating system installation technicians may be as important as providing energy consumption feedback to householders, as they are the often the first people who show the householders how to operate the heating system and set default system settings.
- The electricity energy consumption feedback was not entirely ineffective. One household stopped using their electric shower and electric immersion from the IHD in the house. The house reduced its electricity consumption by 3.6 kWh/day between 2015 and 2016.
- Several households highlighted reasons for the ineffectiveness of the direct and indirect electricity feedback, including (i) lack of engagement with the IHD, (ii) lack of motivation to reduce electricity consumption behaviours, (iii) comprehension issues with information provided, (iv) struggling to engage other house occupants to be more energy conservative and (v) householders having already minimised their electricity consumption through the use of an electricity pre-pay meter.

Chapter 7. Discussion and Conclusions

7.1 Chapter Summary

This chapter summarises the main conclusions of the thesis. Section 7.2 describes the outcomes of each chapter and the relationships between each chapter. Section 7.3 provides concluding remarks and Section 7.4 presents potential future work continuing from this thesis.

7.2 Thesis Discussion

For Ireland to achieve an nZEB building stock by 2040, work is required to be carried out on approximately 2.5 million housing units with 1.9 million housing units in need of an energy efficiency retrofit. The environmental, economic and social impact of this required work on the housing stock is governed not only by the materials and technologies invested into the buildings but also the interrelationships between the people occupying the buildings and how they interact with and operate the materials and technology invested into the buildings. This thesis investigated the environmental, economic and social impacts of residential buildings in Ireland moving towards nZEB standards by examining the interrelationships between the operational energy demand practices in buildings, the people occupying buildings and the materials and technology used in the construction/retrofit of the buildings (Figure 7.1)

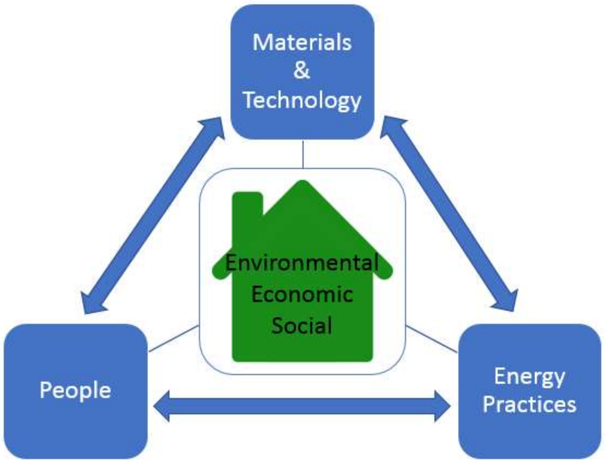

Figure 7.1: Flowchart of research which aimed to investigate the environmental, economic and social impacts of residential buildings in Ireland moving towards nZEB standards by examining the interrelationships between the operational energy demand practices in buildings, the people occupying buildings and the materials and technology used in the construction/retrofit of the buildings.

With LCA mandatory in building design in several EU countries [41], a lack of LCA studies in relation to Irish residential buildings and a large range of environmental impacts for buildings designed to a high energy performance standards (see Section 2.2), a standardised comprehensive environmental LCA examining the life cycle breakdown and more accurate environmental intensity values from an Irish context was necessary. In **Chapter 3**, the interrelationship between the materials and technology used in the construction of new buildings and the building operational energy demand from an environmental and economic perspective was the primary focus. A life cycle environmental and economic analysis was used to examine the interrelationship between the materials and technology used in the construction of new buildings designed to past and present building regulations and the operational energy demand of the buildings**.** The environmental and economic life cycle assessment was carried out on semi-detached theoretical case study buildings designed to past and present energy performance standards. For a semi-detached gas heated dwelling designed to 2005 Irish energy performance building regulations, the material and technology impact can account for 11% of the life cycle energy, 19% of the life cycle GWP and 62% of the life cycle cost. Although the cost associated with the construction of a new building in this analysis only accounts for the building costs, it does not account for the acquisition of land which is considered the second highest contributor to the cost of constructing a new house in Ireland [356]. Accounting for (i) electricity generation decarbonisation and increased electricity generation efficiency, (ii) future energy pricing and (iii) discounting operational energy costs, the materials and technology for a semi-detached building designed to the 2005 building regulations in Ireland can account for up to 12% of the life cycle energy, 21% of the life cycle GWP and 35% of the life cycle cost.

For new residential buildings moving towards nZEB energy performance standards, the materials and technology for a semi-detached building can account for up to 36% of the life cycle energy, 100% of the life cycle GWP and 57% of the life cycle cost. These results depend on (i) the heating system employed, (ii) electricity generation decarbonisation and increased efficiency, (iii) increasing future energy pricing and (iv) discounting operational energy costs. As can be seen from the results, a designer's role in selecting appropriate 'green' sustainable materials is highly stressed due to the tightening of energy performance standards to nZEB for new residential buildings. Minimising the environmental and economic impact from the materials and technology used in the construction of new build nZEB residential buildings is becoming equally, if not more, important than the environmental and economic impact from operation of residential buildings**.**

With half a million new dwelling units in Ireland required by 2040, LCA assessments need to be carried out on the designs of homes to minimise the environmental and economic impact from the materials and technology used. Semi-detached buildings currently account for 28% of the Irish housing stock and 18% of the housing units built between 2011 and 2016 [73]. Changes in Irish building planning regulations are making it to easier for multi-storey apartment buildings to be developed [357]. The construction of semi-detached houses may become less common in Ireland in the future with the need for apartments to be a more prevalent form of housing [72]. Moving from a building complying with the 2011 energy performance, thermal fabric and ventilation standards to a building complying with passive house thermal fabric and ventilation standards to achieve nZEB energy performance standards will save an estimated 116.3 TJ/m^2, 0.8 kilotons CO_{2eq}/m^2 and €2.6 million/m^2 over 60 years. This assumes that 10% of the half a million required residential units are semi-detached buildings are split between having either a gas boiler, biomass boiler or heat pump orientated heating system. These savings can be increased further if material ‘hot spots’ in the building design are mitigated through the use of LCA.

For building retrofits, inaccurate assumptions regarding material and technology performance characteristics and energy demand practices of people have been identified for the discrepancies in expected retrofit energy savings. To examine whether social impacts need to start being quantified with economic and environmental indicators in designing and evaluating the sustainability of a residential building energy efficiency retrofit in Ireland, building thermal fabric and heating system retrofit energy efficiency design packages for residential buildings in Ireland were examined in **Chapter 4** incorporating environmental, economic and social indicators. 46,106 occupied Irish housing units are gas heated semi-detached buildings built between 1991 to 2000 [73]. In Section 4.4.1 of **Chapter 4**, the interrelationship between the materials and technology used in the retrofit of existing buildings and the operational energy demand from an environmental and economic perspective was the primary focus. A life cycle environmental and economic analysis was used to examine the interrelationship between the materials and technology used in 35 different retrofit packages for an Irish semi-detached gas heated house constructed between 1991 and 2002 and the operational energy demand of the building. From an economic perspective, the investigation found that investing materials and technology for deep energy efficiency retrofits to be only economically feasible with aid from the government through grants and tax breaks. Currently, a grant worth 50% of the retrofit costs is available to all types of households involved in the SEAI Better Energy Communities Scheme if the house is retrofitted to at least an A3 BER standard. Assuming a government grant covering 50% of the retrofit costs, the two most cost-effective energy efficiency retrofit packages for the theoretical gas heated semi-detached building for a householder were deep retrofits with (i) basic thermal fabric measures and (ii) advanced gas boiler or ASHP heating system measures (Retrofit Package A-S5(a)/(b)). While a ban will be in place from 2025 on the installation of gas boilers in new buildings [358], no such ban has been introduced yet for building retrofits. The two packages led to the building achieving an A2 BER level energy efficiency and saved the householder over 30 years between €76-95/m^2, 895-1059 $kgCO_2/m^2$ and 13.7-15.0 GJ/m^2, assuming all the estimated energy savings are achieved. 22,142 gas-heated semi-detached or end-terraced buildings built between

1991 and 2000 have a BER label [74]. The existing theoretical house examined in this thesis achieved a BER label of C2. There are currently 3,357 C2 rated semi-detached or end-terraced gas heated houses in Ireland with a 300mm cavity that have not being classified as receiving a government grant. Assuming the 3,357 residential buildings have similar building fabric and heating system specifications as the existing semi-detached building examined in this thesis, potential householder savings ranging from €254,000/m^2 to €331,000/m^2, 3006 tCO$_2$/m^2 to 3554 tCO$_2$/m^2 and 46,135 GJ/m^2 to 50,196 GJ/m^2 over 30 years could be achieved if this typology was retrofitted to A2 standards. However, this would require a government investment ranging from €514,000/m^2 to €648,000/m^2. The government are unlikely to provide grant for all 3,357 C2 rated semi-detached or end-terraced gas heated houses to be retrofitted to an A2 BER standard.

The life cycle energy and life cycle GWP results supported having grants available to householders to install an ASHP and/or renewable technology. However, for other environmental indicators evaluated, heat pumps and adding renewable technology were found to be worse in many instances due to the environmental embodied impact of the systems and the environmental impact of the electricity grid. For retrofit steps S-4(b), S-5(a) or S-5(b), the introduction of an ASHP heating system and/or renewable technology resulted in the larger life cycle ODP, life cycle EP, life cycle AP and life cycle POCP impacts. In some energy efficiency retrofit packages, the embodied environmental impact from the introduction of an ASHP and/or renewable technology accounted for the total life cycle ODP, life cycle EP, life cycle AP and life cycle POCP impact.

While Section 4.4.1 of **Chapter 4** found that investing materials into buildings to improve their energy efficiency can be effective in theory from an environmental and economic perspective, Section 4.4.2 of **Chapter 4** examined the social impacts of investing materials and technologies into buildings as part of a retrofit from a householders perspective. The interrelationship between the materials used in the retrofit of existing buildings, the people in the buildings and the operational energy demand practices were examined from an environmental, economic and social perspective for 20 co-operative social housing units in Ireland. Thermal comfort changes based on monitored temperature and RH data was used to represent the social impact of the retrofit. Once the thermal comfort changes together with energy and cost savings were accounted for, 16 of the 20 households experienced a benefit following an energy efficiency retrofit. Only 11 of the monitored houses benefited from the energy efficiency retrofit when only accounting for energy and cost savings. This was due to the 20 households having an average energy savings deficit of 62%. Thus, social impacts from building energy efficiency retrofits need to be quantified. This is to justify the economic and environmental savings deficits that are often found between theoretical and actual energy consumption savings from residential building retrofits.

To be able to accurately predict the environmental, economic and social impacts from an energy efficiency building retrofit, a greater understanding of how and why households use energy within the home is required. However, the way a household uses energy in the home and the energy savings from a material focused energy efficiency retrofit can vary significantly as shown in **Chapter 4.** Buildings are complex socio-technical systems [203] with their energy use affected by the interrelationships between the physical performance of the fabric, building systems, the occupants' understanding of the building systems, expectations and perception of comfort and occupants habitual behaviours [204]. To help understand the energy use and energy savings of the householders following the energy efficiency retrofit, **Chapter 5** deployed the heuristic of energy cultures to examine the interrelationship between the materials and technology used in the retrofit of existing buildings, the people in the buildings and the operational energy demand practices of people in 20 co-operative social housing units in Ireland. An energy cultures framework was used to examine sustainable related outcomes (i.e. building energy use and the internal environment) based on the interrelationships between (i) building material conditions, (ii) energy demand practices, (iii) the attitudes, perceptions and social norms of householders and (iv) a material focused energy efficiency retrofit.

The energy cultures framework was found to be effective in framing interdisciplinary research on energy use before and after retrofitting. Structuring the collected qualitative and quantitative data in the ECF helped to identify possible demand side factors influencing both the energy consumption and energy savings (or lack thereof) for the set of monitored case study buildings. For example, the change in electric immersion water heating practices (ECF Element 3), caused by the change in gas boiler power (ECF Element 1), brought about change in the electricity use of householders. Changes in the material conditions of the case study houses from an energy efficiency retrofit resulted in shifts in householders' perceptions concerning energy, novel forms of post-retrofit energy use, improved household thermal comfort and evidence of pre-retrofit habits and routines that persisted following the retrofit.

The ECF is well suited for investigating empirically how changes in one of the elements of energy culture – in this case altered material conditions brought about by an energy retrofitting programme – influence other elements of energy culture and the influence energy culture elements have on household energy consumption. Although the small sample size of the study in **Chapter 5** cannot justify adopting a sociotechnical approach to understand how the interrelationships between buildings and their occupants are driving energy consumption into retrofitting programmes, it adds to the growing calls for such an approach to be implemented for energy savings to be realised [337], [338]. If a culturally sensitive sociotechnical approach is applied on a national scale in retrofit projects, it could help to (i) strengthen the evidence for policy-makers in building retrofitting, (ii) inform future targeted building retrofit and environmental mitigation policy measures for different groups of buildings and people, including economically vulnerable parts of the population, (iii) develop hands-on change initiatives and demonstrator projects that seek to transform both householders' attitudes, perceptions and social norms as well as their daily practices and (iv) draw attention to energy-cultural diversity to aid countries in meeting their energy efficiency and carbon reduction targets, including EU member states committed to implementing the EU's Energy Union

To assess if energy consumption feedback and information on energy demand practices would elicit any changes in household energy use and help reduce the environmental and economic impact from household energy use, an energy saving initiative (ESI) was carried out on the monitored case study buildings. The effectiveness of the ESI was presented in **Chapter 6**. The ESI focused on four energy consumption end use areas: (i) SH services, (ii) DHW heating services, (iii) domestic appliances and (iv) cooking services. This was implemented for a group of 14 households by providing direct and indirect feedback on electricity consumption using an interactive online web dashboard, a demonstration on how to use the online dashboard and detailed monthly electricity consumption reports. Appliance usage and cooking energy saving tips were included as part of the monthly electricity reports. Energy savings information/tips for SH and DHW heating were provided as part of the gas consumption and internal environment feedback reports following the energy efficiency retrofit.

Non-time-consuming feedback was the most effective feedback. Any tips/information given to the householders on how to reduce gas and electricity consumption that involved investing time and continuous engagement were mostly unsuccessful. The most effective feedback was advising householders on the correct DHW temperature setpoint as the temperature setpoints were very set high in some houses. The households that reduced their gas consumption and DHW temperature setpoint settings saved on average 1.6 kWh/day during the non-heating season. The average annual gas and electricity energy cost savings in the estate in 2016 following the retrofit in 2015 were €141 and €140, respectively. For the households involved in the ESI study, they saved, on average, €18 in gas energy over the course of a year in 2017. The electricity feedback was for the most part ineffective. Thus, in the context of this study, retrofitting technology was more effective at eliciting changes in energy consumption compared to energy saving feedback information.

7.3 Conclusions

The aim of this thesis was to investigate the environmental, economic and social impacts of residential buildings in Ireland moving towards nZEB standards by examining the interrelationships between the operational energy demand practices in buildings, the people occupying buildings and the materials and technology used in the construction/retrofit of the buildings. To investigate this, the environmental, economic and social impacts of theoretical and monitored semi-detached and terraced houses were examined considering (i) past and present building regulations, (ii) the materials and technology employed in the buildings, (iii) future electricity generation fuel mix, (iv) future energy pricing, (v) discounting operational energy costs, (vi) the space heating, domestic water heating and appliance energy demand practices of people occupying the buildings and (vi) people's attitudes, perceptions and social norms regarding energy consumption and the environment.

The key research outcomes of the thesis are summarised as:

- With the tightening of energy performance standards for new residential buildings, a designer's role in sustainably selecting appropriate 'green' materials is highly stressed. As new residential buildings move towards nZEB energy performance standards and depending on the (i) heating system employed, (ii) electricity generation decarbonisation and increased efficiency, (iii) future energy pricing and (iv) discounting operational energy costs, the materials and technology for a semi-detached building can account for up to 36% of the life cycle energy, 100% of the life cycle GWP and 57% of the life cycle cost. Minimising the environmental and economic impact from the materials and technology used in the construction of new build nZEB residential buildings is becoming equally if not more important than the environmental and economic impact from the occupant's operation of residential buildings**.**

- For nZEB new builds, having a superstructure with a high thermal mass and air-tightness is more effective than relying on renewable technology to mitigate building energy demand. However, a concrete based superstructure, including a cavity block wall with a concrete foundation, is the main contributor to the embodied environmental and economic impact of semi-detached buildings. If concrete is to continue being the main superstructure form in Irish construction practices, its environmental impact needs to be further mitigated. From an environmental perspective considering energy and GWP, a heating system should employ a biomass boiler or heat pump rather than a CHP or gas boiler in nZEB buildings in Ireland.
- For semi-detached gas heated houses in Ireland constructed between 1991 and 2002, the operation of the building has a greater life cycle energy and life cycle GWP impact compared to the materials and technology invested from the retrofit, even if the building moves towards new build nZEB standards. Unless the buildings achieve an nZEB new build standard, the operation of the building has a greater impact compared to the materials and technology invested from the retrofit from a life cycle cost, life cycle AP, life cycle EP, and life cycle POCP.
- Deep energy efficiency retrofits are economically feasible with aid from government through grants and tax breaks for Irish semi-detached gas heated houses constructed between 1991 and 2002. Without these incentives, only shallow retrofits are economically feasible.

- If Ireland is to continue moving to a more electrified economy which will increase the demand for electricity, the environmental impact of electricity generation for GWP, ODP, EP, AP and POCP needs to be continuously monitored and mitigated to ensure Ireland achieves its goal of a sustainable economy by 2050.
- How people consume energy and save energy within a house can vary significantly from house to house even with similar building materials and technology. Following the retrofitting of the monitored case study households, the gas energy consumption for the different construction types had a large variability. The 1994 mid-terrace household gas consumption ranged from 3432 MJ/m^2 to 5346 MJ/m^2, 4093 MJ/m^2 to 8158 MJ/m^2 for the 1994 end-terrace households, 3610 MJ/m^2 to 7238 MJ/m^2 for the 2000 mid-terrace households, 2443 MJ/m^2 to 5338 MJ/m2 for the 2000 end-terrace households and 6003 MJ/m2 to 7395 MJ/m2 for the 2000 semi-detached households. On average the households experienced an energy savings deficit of 62%.
- Social benefits from energy efficiency building retrofits need to be quantified as the theoretical energy and cost savings from a building energy efficiency retrofit may not be achieved. Once the thermal comfort social indicators (temperature and RH) were accounted for together with energy and cost for 20 housing units which underwent an energy efficiency retrofit, 16 of the 20 households experienced a benefit following an energy efficiency retrofit. Only 11 of the monitored houses benefited from the energy efficiency retrofit when only accounting for energy and cost savings. This was due to the 20 households having an average energy savings deficit of 62%.
- To be able to accurately predict the environmental, economic and social impacts from an energy efficiency building retrofit, a greater understanding of how and why households use energy within the home is required. To help understand the interrelationships of the energy consumption of the monitored residential buildings, the people occupying the buildings and the materials used in the construction/retrofit of the buildings, the energy cultures framework was found to be useful for (i) observing how the energy cultures of householders were affected by an energy efficiency retrofit and (ii) identifying factors that may be influencing the energy consumption and the success (or

lack thereof) of the retrofitting efforts in reducing energy consumption. This research adds to the growing calls for adopting a sociotechnical approach to retrofitting programmes for energy savings to be realised [337]. If a sociotechnical approach is applied on a national scale in retrofit projects, it could (i) strengthen the evidence for policy-makers in building retrofitting, (ii) understand the environmental, economic and social impacts of various building retrofits design packages for different groups of buildings and people, (iii) inform future targeted building retrofit and environmental mitigation policy measures for different groups of buildings and people, including economically vulnerable parts of the population, (iv) develop hands-on change initiatives and demonstrator projects that seek to transform both householders' attitudes, perceptions and social norms as well as their daily practices and (v) draw attention to energy-cultural diversity to aid countries in meeting their energy efficiency and carbon reduction targets, including EU member states committed to implementing the EU's Energy Union.

- Following changes to the building material and heating system technology as part of energy efficiency retrofit in 2015, the average gas and electricity energy cost savings in the monitored housing estate in 2016 were €141 and €140, respectively.
- Efforts to elicit changes in the energy use practices of householders and in turn their energy consumption levels by providing householders feedback on their energy usage and information on energy demand practice were unsuccessful for the most part. The most effective feedback was to advise householders on the correct DHW temperature setpoint (as the temperature setpoints were very set high in some houses). This type of feedback could be characterised as non-time consuming as the householders only had to make one adjustment to their DHW thermostat settings. For the households involved in the ESI study, they saved, on average, €18 in DHW gas energy over the course of a year in 2017. The electricity feedback was for the most part ineffective. Any tips/information given to the householders on how to reduce gas and electricity consumption that involved investing time and continuous engagement were mostly unsuccessful.

- Several households highlighted reasons for the ineffectiveness of the direct and indirect electricity feedback including lack of engagement with the IHD, lack of motivation to reduce electricity consumption behaviours, comprehension issues with information provided, struggling to engage others in household to be more energy conservative and electricity pre-pay meter had already minimised electricity consumption.

7.4 Future Work

In this thesis, a life cycle assessment study was carried out on new build semi-detached houses with a concrete based superstructure as they moved towards Irish nZEB standards. O'Reilly [286] examined the environmental and economic life cycle impact of an Irish semi-detached house designed using three different superstructure types. The semi-detached buildings were designed to an A3 BER standard using a concrete-based superstructure, timber-based superstructure and light weight steel-based superstructure. Further life cycle assessments for different Irish typologies designed to nZEB energy performance standards need to be carried out considering multiple environmental, economic and social indicators. This to ensure Irelands new buildings help in transitioning to a sustainable low carbon economy by 2050. Further research is also needed in identifying suitable environmental, economic and social indicators, indicator weightings and an assessment framework for developing sustainable Irish buildings. Additionally, the impact of future climate scenarios on energy demand and the risk of overheating in future climates, which has been assessed for net zero UK dwellings [359], was not evaluated as part of this research thesis and should be explored for different thermal fabric and heating system designs.

While the case study buildings examined different thermal fabric and heating system design strategies for a new build semi-detached residential building from an environmental and economic perspective in **Chapter 3,** the optimum insulation thicknesses for the building elements from an environmental and economic perspective were not assessed. From a life cycle environmental perspective, Lowe et al. [360] found that if the optimal thickness of insulation in a building is underestimated, the environmental impact will be greater over the building lifespan. However, Ucar & Balo [361] found that if the optimal thickness of insulation in a building is overestimated, the cost impact can be greater over the building lifespan.

The optimal insulation thicknesses over a building lifespan from an environmental and economic perspective will also be susceptible to future energy prices, electricity generation decarbonisation and increased efficiency of electricity generation. An investigation into the how these different parameters influence the optimal insulation thicknesses in buildings constructed in Ireland needs to be carried out. Furthermore, Ireland’s climate is expected to change into the future. External temperatures are expected to increase in Ireland by 0.9-1.7°C by 2050 [362]. How these changes in temperatures are expected to impact the performance of heating systems (e.g. an air source heat pump season performance factor is dependent on the external temperature [363]), optimum building insulation thicknesses and the susceptibility of Irish buildings to overheating in the future should also be examined.

35 different retrofit packages for an Irish semi-detached gas heated house constructed between 1991 and 2002 were assessed in this thesis. It was found that without economic incentives such as government grants and tax breaks, only shallow retrofits were economically feasible for this typology. There are 33 other typical existing Irish residential typologies with various building elements and heating systems [20]. Multiple retrofit packages need to be assessed for these typologies considering multiple environmental, economic and social indicators to see what the best options for Irish householders and society are as a whole.

The social impact of retrofit packages for improving the Irish residential housing stock needs to be quantified to justify government investment in building energy efficiency measures. Particularly where projected energy and cost savings are not achieved through energy consumption reduction and where it is not economically justifiable for householders to retrofit to high energy performance standards. Although mixed results have been found when trying to quantify the social impacts of building energy performance investments, the European Foundation for the Improvement of Living and Working Conditions [364] estimated the cost of people living in inadequate housing in the EU to be nearly €194 billion. Removing the inadequacy of houses would cost €295 billion. This analysis quantifies the adequacy of housing based on several factors including heating problems. The study estimated the €1.24 billion investment needed for Ireland to have an adequate housing stock would take 22 years to pay back based on the direct savings made in the healthcare sector. However, the investment could be paid back in a year if indirect medical savings were accounted for. In a different study on English social housing, improving the energy efficiency of social housing in England was found, on average, to have reduced the health service use by £94.79 over 6 months [167]. This cost saving would payback within 20 years through direct health service savings. For housing in low income areas in Wales, improving the energy efficiency of housing found no explicit cost reductions to the health service due to non-significant changes in emergency admissions for cardiorespiratory conditions [166]. In Ireland, SEAI in conjunction with the Irish National Health Service are currently examining whether a home energy efficiency retrofit helps in improving the living conditions of people living with chronic respiratory conditions [315]. However, further research is required in Ireland on the quantifying the health impacts from building energy efficiency improvements as they have been found to improve the social and mental health of the building occupants [166].

An average energy savings deficit of 62% from a material and technology focused retrofit was found for the monitored set of houses examined in this thesis. Other studies have found the average energy savings deficit to range from 14% to 98% [45], [46], [55], [47]–[54]. Reasons for the discrepancies in actual energy usage to theoretical energy usage of engineering energy demand models can be categorised as material and technology performance characteristics, malfunctioning technology and energy demand practices. However, studies examining how much of the energy savings deficits are due to the differences in the assumptions of standard assessment procedures and the actual buildings are limited. Further studies are needed to identify the main factors causing the differences in the theoretical and actual energy consumption. If this is done for different building typologies inhabited by different demographic and socio-economic groups, this would help identify areas where standard assessment procedure protocols could be improved. Improving the accuracy of standard assessment procedure will aid in developing policies that move from a generalised approach to individualized that understands specific groups and their needs.

As noted in the discussion of **Chapter 4**, the energy savings for some of the households were found to be affected by a desire for a higher thermal comfort. However, estimating how much of the energy savings deficit experienced by the households was accounted for by the desire for a higher thermal comfort was not an objective of this study. Of the reviewed literature, only seven studies detailed how much of the energy savings shortfall is accounted for by temperature take back [48], [51], [141], [146], [316]–[318]. Opinion was divided on the significance of the temperature take back in energy savings shortfall from an energy efficiency retrofit with some estimating impacts ranging from 10% to 82% [48], [316]–[318] while others found the impact to be less than 5% [46], [51], [141], [146]. However, there were issues with the methodologies and results of these seven studies such as (i) limited monitoring periods [46], [48], [319], (ii) small sample sizes [147], (iii) limited details of data collection methodologies [316], (iv) houses receiving different retrofit solutions, [46], [48], [316]–[319], (v) no before and after retrofit data [141], (vi) results based on thermostat settings [141], [317] and temperature spot measurements [51] and no attempts to explain whether changes in temperature are due to the physical retrofit of the building or changes in the behaviour of how the occupants operate their homes [48], [316]–[319]. This area of research needs further study to assess how much temperature take back accounts for energy savings deficits.

The attitudes, perception and social norms of householders in relation to the environment were examined. No identifiable correlation was found between the social norms and environmental attitudes regarding energy conservation of the householders in this thesis and their energy usage. Furthermore, many of the householder’s attitudes and social norms were not impacted by the energy efficiency retrofit. However, this may be related to the small sample size of houses monitored. Further research is needed to examine whether there is a link between changing materials conditions via an energy efficiency retrofit and changes in people attitudes and social norms in relation to the environment. Additional data was gathered which was not included in this research thesis from a set of rural houses in Ireland. A similar data collection procedure was carried out on these rural houses as the co-operative social housing units examined in this thesis. For the 12 rural houses, data was gathered using (i) pre-retrofit and post-retrofit participant surveys, (ii) installation of data-logging instrumentation, and (iii) monthly readings of electricity meters and oil usage levels. This data will be analysed to examine the interrelationships between the material conditions, energy usage and attitudes, perceptions and social norms of the householders and how/if they differ from the set of urban social co-operative houses examined in this thesis.

Prompting changes in the energy consumption of the householders was found to be more effective by investing in materials and technology rather than providing energy consumption feedback. However, the ESI study carried out in this thesis was limited by its sample size, format of feedback and changes in fuel price tariffs. Further research is required on a larger sample size with different demographic and socio-economic groups receiving more automated disaggregated energy consumption and IAQ feedback to assess whether it elicits any changes in household energy consumption.

All in all, however, much of the research in the Irish built environment is limited by having small sample sizes or a lack of resources to be able to carry out large empirically-driven survey or monitoring projects. These issues have been noted for built environment research in the UK [365], [366]. For the type of potential environmental and economic savings for new build and buildings retrofits reported in this thesis to be realised, significant investment is needed in energy demand research in the Irish built environment to be able to fully understand the interrelationship between building materials and technology, people occupying the buildings and energy demand practices in the buildings.

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Appendix A. Abbreviations

A: Before Advice
AAHP: Air-to-Air Heat Pump
AC: Air Conditioning
$\mathrm{ACT_{THE}}$: Actual
$\mathrm{ACT_{POST}}$:
ADV: Advanced Retrofit Measure
ALU: AluClad Window and Door Measure
AP: Apartment
ASHP: Air Source Heat Pump
AU: Austria
AVG: Average
AWHP: Air-to-water heat pump
B: After Advice
BAS: Basic Retrofit Measure
BD: Bedroom
BER: Building Energy Rating
BG: Belgium
BR: Building Regulations
BU: Buildings
C: Day of Feedback Questionnaire
CDD: Cooling Degree Day
CGB: Condensing Gas Boiler
CH: China
CHP: Combined Heat and Power
CK: Cooking
CLI: Climate
CLT: Cross Laminated Timber
CO: Cost-Optimal Method Employed
CON: Concrete
CONS: Construction
CPC: Carbon Performance Coefficient
CTC: Cradle-to-Cradle
CTGA: Cradle-to-Gate
CTGR: Cradle-to-Grave
CTS: Cradle-to-Site
CW: Pumped Cavity Wall Insulation
CZR: Czech Republic
D: End of Study
DEAP: Dwelling Energy Assessment Procedure
DG: uPVC Double Glazed Windows and uPVC Doors
DH: District Heating
DHW: Domestic Hot Water
DK: Denmark
DT: Detached
EAHP: Exhaust Air Heat Pump
EC: Embodied Carbon
ECF: Energy Cultures Framework
EE: Embodied Energy
EED: Energy Efficiency Directive
EL: Electricity
ENPC: Energy Performance Certificate
EP: Energy Practices
EPC: Energy Performance Coefficient
EPG: Energy Performance Gap
ESD: Energy Savings Deficit
ESI: Energy Saving Initiative
ETR: End-Terrace
ETSC: Evacuated Tube Solar Collector
EU: European Union
EWI: External Wall Insulation
EXT: Existing Building
FB: Fabric
FBR: Front Bedroom
FL: Finland
FR: France
G: Green Insulation Measure
GB: Gas Boiler
GHG: Greenhouse Gas
GHP: Ground Heat Pump
GSHP: Ground Source Heat Pump
GWP: Global Warming Potential
HDD: Heating Degree Day
HP: Heat Pump
HRE: Heat Recovery Efficiency
HS: Heating System
HVAC: Heating, Ventilation and Cooling
IHD: In-House Display
IPCC: Intergovernmental Panel on Climate Change
IT: Italy
IWI: Internal Wall Insulation
JO: Insulation on Joists of Roof
KT: Kitchen
LC AC: Life Cycle Acidification
LC AT: Life Cycle Aquatic Toxicity
LCB: Life Cycle Boundary
LC CC: Life Cycle Climate Change
LC CO_2: Life Cycle CO_2
LC EN: Life Cycle Energy
LC EU: Life Cycle Eutrophication

LC CED: Life Cycle Cumulative Energy Demand
LC CED_{nr}: Life Cycle Cumulative Energy Demand Non-Renewable
LC FE: Life Cycle Freshwater Eutrophication
LC GHG: Life Cycle Green House Gas Emissions
LC GWP: Life Cycle Global Warming Potential
LC HT: Life Cycle Human Toxicity
LC NRPE: Life Cycle Non-Renewable Primary Energy
LC OD: Life Cycle Ozone Depletion,
LC PM: Life Cycle Particulate Matter Formation
LC TT: Life Cycle Terrestrial Toxicity
LEH: Low Energy House
LPG: Liquefied Petroleum Gas
LT: Lighting
LWT: Light Weight Timber
M: Market
MCPV: Multi-crystalline Photovoltaics
MF: Multi-Family Building
MN: Manual Operation
MV: Mechanical Ventilation
MVHR: Mechanical Ventilation with Heat Recovery
NON-Res: Non-Residential Building
NR: Norway
NTH: Netherlands
NV: Natural Ventilation
nZEB: Nearly Zero Energy Building
OC: Operational Carbon/Global Warming Potential
OE: Operational Energy
OS: Operational Settings
PH: Passive House
POST: Post-Retrofit
PR: Schedule and Thermostat
PR/MN: Schedule and Thermostat and Manual Operation
PRE: Pre-Retrofit
PRT: Portugal
PSR: Passive Regulations
PV: Photovoltaics
PVC: PVC Window and Door Measure
REEM: Retrofit Energy Efficiency Measure
REU: Representative of EU
RM: Romania
RN: Renewable Technology
SAV: Savings
SC: Solar Collectors
SCD: Social Demographic
Scenario A: SH
Scenario B: SH and DHW
Scenario C: SH, VT, Pumps and fans for SH and VT, DHW and LT
Scenario D: All end uses excluding SH, DHW and plug loads
SD: Semi-Detached
SFH: Single Family House
SF: Single Family Building
SH: Space Heating
SI: Super insulated
SIM: Simulated Data
SL: SlovakiaSP: Spain
SPF: Specific Fan Power
STE: Steel
SW: Sweden
TAS: Thermal Analysis Software
TG: uPVC Triple Glazed Windows and uPVC Doors
TGD: Technical Guidance Document
TH: Terraced House
THE: Theoretical
THE_{PRE}:
THE_{POST}:
TIM: Timber
TM: Temperature
TR: Terraced
TY: Turkey
UK: United Kingdom
UNK: Unknown
VT: Ventilation
WM: Warm Water Solar Collector Units
WD: Wood

Appendix B. New Build LCA Embodied Intensities

Ref.	Material	EE Intensity (MJ/kg)	EC Intensity (kgCO$_{2eq}$/kg)
[109]	Aggregate	0.083	0.0052
[109]	Aluminium Coil	155	9.18
[109]	Cast Aluminium	159	3.1
[109]	Concrete Block 10 MPa	0.67	0.078
[109]	Copper	57	3.81
[275]	Cotton	30.66	3.28
[267]	Evacuated Tube Solar Collectors* (per m^2)	1689.2	111.6
[109]	Expanded Polystyrene	88.6	3.29
[109]	Fibre Cement Panel	10.4	1.09
[109]	Fibreglass	28	1.35
[109]	General Concrete	0.75	0.107
[109]	General Plastic	80.5	3.31
[109]	General Purpose Polystyrene	86.4	3.43
[275]	Glass Fibre	44.4	2.64
[109]	High Density Polyethylene	76.7	1.93
[109]	Iron	25	2.03
[109]	Lead	25.2	1.67
[109]	Low Density Polyethylene	78.1	2.08
[109]	Low Density Polyethylene Film	89.3	2.6
[109]	Mastic Sealant-Synthetic Rubber	91	2.85
[109]	Mineral Wool	16.6	1.28
[109]	Mortar (1:1:6 Cement:Lime:Sand mix)	1.11	0.174
[109]	Mortar (1:3 Cement:Sand mix)	1.33	0.22
[266]	Multi-crystalline Photovoltaics* (per m^2)	3908.9	553.8
[275]	Nickel Pigment Coating	85	5.63
[109]	Nylon 6	120.5	9.14
[109]	Oriented Strand Board	15	0.45
[109]	Paint (Double Coat)	21	0.87
[109]	Paint (Triple Coat)	31.5	1.31
[109]	Plaster	1.8	0.13
[109]	Plasterboard	6.75	0.39
[109]	Plywood	15	0.45
[109]	Polyethylene	83.1	2.54
[367]	Polyisocyanurate	55.11	2.48
[109]	Polypropylene Orientated Film	99.2	3.43
[109]	Polyurethane Rigid Foam	101.5	4.26
[109]	Precast Concrete (32/40 MPa)	1.48	0.19
[109]	Precast Concrete (40/50 MPa)	1.5	0.18
[109]	Precast Concrete (8/10 MPa)	1.15	0.13

[109]	Primary Glass	15	0.91
[109]	PVC General	77.2	3.1
[109]	PVC Pipe	67.5	3.23
[109]	Rockwool	16.8	1.12
[109]	Sand	0.0081	0.0051
[109]	Sawn Hardwood	10.4	0.24
[109]	Sawn Softwood	7.4	0.2
[109]	Stainless Steel	56.7	6.15
[109]	Steel	20.1	1.46
[109]	Steel Bar	17.4	1.4
[109]	Steel Section	21.5	1.53
[109]	Steel Wire	36	3.02
[109]	UPVC Film	69.4	3.16
[109]	Vinyl Flooring	65.64	2.29
[109]	Vitrified Clay Pipe DN 100 & DN 150	6.2	0.46

Appendix C. Retrofit LCA Embodied Intensities

Ref.	Material/Component	CED	GWP	ODP	AP	EP	POCP	
		MJ	kgCO$_2$eq	kg CFC11 eq	kg SO$_2$ eq	kg (PO$_4$)$^{3-}$ eq	kg C$_2$H$_4$ eq	Functional Unit
[368]	Mineral Wool Insulation	2.55E+02	1.22E+01	1.20E-06	6.31E-02	1.05E-02	2.38E-03	m^3
[369]	Rockwool Insulation	2.13E+01	1.40E+00	2.30E-08	7.00E-03	7.30E-04	6.50E-04	m^2
[370]	Double Glazed uPVC Window	1.28E+03	6.37E+01	4.01E-06	3.11E-01	3.55E-02	1.72E-02	m^2
[371]	Triple Glazed uPVC Window	1.59E+03	7.64E+01	1.18E-06	3.03E-01	3.75E-02	2.24E-02	m^2
[372]	Triple Glazed AluClad Window	1.75E+03	5.59E+01	6.60E-06	4.42E-01	1.20E-01	2.07E-02	m^2
[256]	uPVC	6.62E+01	4.71E+00	8.79E-08	1.65E-03	2.95E-02	4.23E-03	kg
[256]	Glass Production	1.44E+01	1.12E+00	9.77E-08	9.78E-03	1.36E-03	3.46E-03	kg
[256]	Wooden-Aluminium Door Production, Outer	2.80E+03	1.26E+02	6.12E-06	8.09E-01	2.42E-01	4.76E-02	m^2
[373]	Expanded Polystyrene Foam Insulation	1.38E+03	4.71E+01	2.97E-09	1.19E-01	1.10E-02	2.50E-01	m^3
[374]	Wood Fibre Insulating Boards	5.42E+03	-1.64E+02	8.75E-10	1.96E-01	3.16E-02	2.81E-02	m^3
[375]	Paint	4.10E+00	2.13E-01	2.21E-08	1.15E-03	2.42E-04	9.44E-05	m^2
[256]	Glass Fibre Production	4.12E+01	2.25E+00	2.12E-07	1.43E-02	4.00E-03	5.10E-04	kg
[256]	Aluminium Alloy Production	7.33E+01	5.72E+00	2.36E-07	3.02E-02	9.21E-03	1.91E-03	kg
[256]	PVC Production	6.19E+01	2.07E+00	1.44E-08	5.74E-03	9.10E-04	3.35E-04	kg

[256]	Silicone Production	6.07E+01	3.04E+00	1.96E-06	1.32E-02	4.23E-03	4.97E-04	kg
[376]	Phenolic Insulation	2.97E+03	9.86E+01	7.83E-09	2.00E-01	2.69E-02	9.90E-02	m^3
[377]	Plasterboard	4.22E+01	2.50E+00	6.10E-08	1.20E-02	1.10E-03	9.40E-04	m^2
[256]	Polypropylene Production	7.51E+01	1.98E+00	8.29E-10	6.21E-03	6.47E-04	4.25E-04	kg
[378]	Mineral pre-made mortar: rendering mortar	4.42E+00	3.94E-01	2.52E-09	9.59E-04	9.90E-05	7.65E-05	kg
[379]	Skim coat	4.71E+00	2.32E-01	1.03E-08	5.53E-04	5.26E-05	6.05E-05	m^2
[380]	Adhesive Mortar	1.01E+01	6.38E-01	5.14E-09	2.03E-03	1.82E-04	1.92E-04	kg
[256]	Gas Boiler	6.17E+03	4.74E+02	2.51E-05	4.16E+00	2.48E+00	2.61E-01	Unit
[256]	Brine to Water Heat Pump	8.19E+03	1.56E+03	3.04E-03	1.00E+01	2.80E+00	4.80E-01	Unit
[256]	Evacuated Solar Tube Collector	1.49E+03	1.00E+02	6.83E-06	1.58E+00	9.34E-01	6.58E-02	Unit
[256]	Expansion Vessel	3.34E+02	2.35E+01	1.14E-06	1.12E-01	5.00E-02	8.78E-03	Unit
[256]	Pump	1.07E+02	1.70E+01	8.28E-07	1.77E-01	7.91E-01	9.47E-03	Unit
[256]	Photovoltaic Panel	3.34E+03	2.05E+02	2.48E-05	9.97E-01	4.52E-01	4.70E-02	m^2
[256]	Photovoltaic Panel Mounting System	6.76E+02	6.10E+01	1.93E-06	3.35E-01	2.67E-02	2.19E-02	m^2
[256]	Photovoltaic System Invertor	3.45E+03	2.32E+02	1.64E-05	3.41E+00	2.66E+00	2.32E-01	Unit
[256]	250 litre Stainless Steel Hot Water Tank	4.72E+03	3.38E+02	1.88E-05	1.64E+00	8.15E-01	1.42E-01	Unit

[256]	Ireland High Voltage Electricity Production, Hard Coal	2.97E+00	3.01E-01	1.01E-09	1.90E-03	4.36E-04	7.47E-05	MJ
[256]	Ireland High Voltage Electricity Production, Oil	3.93E+00	2.55E-01	4.73E-08	5.04E-03	1.30E-04	2.03E-04	MJ
[256]	Ireland High Voltage Electricity Production, Natural Gas Combined Cycle Power Plant	2.16E+00	1.05E-01	7.56E-09	4.23E-05	4.86E-06	5.16E-06	MJ
[256]	Ireland High Voltage Electricity Production, Peat	3.04E+00	2.85E-01	4.58E-10	8.11E-04	5.95E-05	2.89E-05	MJ
[256]	Ireland High Voltage Electricity Production, Wind<1MW	-1.03E+00	3.47E-03	1.76E-10	1.93E-05	9.55E-06	1.43E-06	MJ
[256]	Ireland High Voltage Electricity Production, Wind>3MW	-1.01E+00	5.81E-03	3.59E-10	5.58E-05	3.50E-05	3.22E-06	MJ
[256]	Ireland High Voltage Electricity Production, Wind1-3MW	-1.03E+00	3.64E-03	2.42E-10	2.02E-05	9.91E-06	1.41E-06	MJ
[256]	Ireland High Voltage Electricity Production, Hydro Pumped Storage	-1.02E+00	4.30E-03	2.59E-10	3.17E-05	1.82E-05	2.02E-06	MJ
[256]	Ireland High Voltage Electricity Production, Hydro Run-of-River	2.66E+00	2.34E-01	7.55E-09	8.37E-04	1.74E-04	3.41E-05	MJ
[256]	Ireland High Voltage Electricity Production, Waste-Blast Furnace Gas	-1.04E+00	1.20E-03	8.46E-11	4.76E-06	1.92E-06	3.01E-07	MJ
[256]	Heat Production, Natural Gas, at boiler <100kW	1.14E+00	6.34E-02	5.53E-09	5.71E-05	1.12E-05	7.59E-06	MJ

[256]	Heat Production, Coal briquette, 5-15 kW Stove	7.39E+06	1.29E-01	1.84E-09	7.32E-04	1.11E-04	2.28E-04	MJ
[256]	Heat Production, Wood Logs, 6 kW Wood Heater	2.23E+00	9.95E-03	5.44E-10	6.38E-05	2.46E-05	4.67E-06	MJ

Appendix D. Instrumentation Specifications

EL-USB-2+

EasyLog®

High Accuracy Temperature, Humidity and Dew Point Data Logger

- -35 to +80°C (-31 to +176°F) and 0 to 100%RH measurement range
- Stores over 16,000 readings for both temperature and humidity
- EasyLog software available as a free download
- Logging rates between 10 seconds and 12 hours
- Immediate and delayed logging start
- User-programmable alarm thresholds for both temperature and humidit
- Status indication via red/green LEDs
- Environmental protection to IP67

This standalone data logger measures and stores over 16,000 temperature and humidity readings from -35 to +80°C (-31 to +176°F) and 0 to 100%RH range at a resolution of 0.5°C (1°F) and 0.5%RH.

The user can easily set up the logger and view downloaded data by plugging the data logger into a PC's USB port and using the free EasyLog software. Data, including calculated dew point, can then be graphed, printed and exported to other applications for detailed analysis.

The data logger is supplied with a lithium metal battery, giving up to three years' logging life. The logger is protected against ingress from water and dust to IP67 standard when the cap is fitted.

SPECIFICATIONS

Temperature	**Measurement range**	-35°C to 80°C (-31°F to 176°F)
	Internal resolution	0.5°C (1°F)
	Accuracy (overall error)*	0.45°C (0.86°F) typical (5 to 60°C)
	Long term stability	<0.02°C (0.04°F) / year
Relative Humidity	**Measurement range**	0 to 100%RH
	Internal resolution	0.5%RH
	Accuracy (overall error)*	2.05%RH typical (10 to 90%RH)
	Long term stability	<0.25%RH / year
Dew Point	**Accuracy (overall error)***	1.5°C typical (-35 to 80°C, 40 to 100%RH)
Logging rate		User selectable between 10 seconds & 12 hours
Operating temperature range		-35 to +80°C (-31 to +176°F)
Battery life		3 years (at 25°C and 1 minute logging rate)
Readings		16,382 temperature, 16,382 relative humidity
Dimensions		108 x 25 x 22mm (4.25 x 0.98 x 0.86")

* The overall error takes in to account the sensor accuracy (as shown on page 3) and the resolution of the data logger

ACCESSORIES

BAT 3V6 1/2AA	Replacement battery
EL-DataPad	Handheld data logger programmer & collector

INCLUDED IN THE BOX

BAT 3V6 1/2AA	Battery
EL-USB Wall Bracket	Mounting Bracket

CALIBRATION CERTIFICATES NOW AVAILABLE

Lascar now offers a Traceable Calibration Certificate Service on Temperature Data Loggers. Using reference equipment which has been calibrated by a UKAS/NIST accredited laboratory and using apparatus traceable to national or international standards. For more information, please see **www.lascarelectronics.com**.

EL-USB-2+

High Accuracy Temperature, Humidity and Dew Point Data Logger

EL-WIN-USB

Lascar's EasyLog control software is available as a free download from www.easylogusb.com. Easy to install and use, the control software is compatible with 32-bit and 64-bit versions of Windows 7, 8 & 10. The software is used to set up the logger, download, graph and annotate data or export in Excel, PDF and jpeg formats.

The software allows the following parameters to be configured:

- Logger name
- Measurement parameter (°C or °F)
- Logging rate (user selectable between 10 seconds and 12 hours)
- High and low alarms
- Immediate and delayed logging start

Download the latest version of the software free of charge from www.easylogusb.com

LED STATUS INDICATION

The EL-USB-2 features two green/red LEDs, one to represent temperature measurement and the other to represent humidity measurement. Each is clearly marked on the logger. To save power, the status indication alternates between the two channels every 10 seconds. First you will see the status of the temperature channel and 10 seconds later you will see the status of the RH channel and so on.

In normal operation the green LED will flash, but will change to red if an alarm condition has been triggered. Using EL-WIN-USB it is possible to set the alarm to remain active even if the reading has returned to normal, in which case the alarm LED will continue to flash red. This 'Hold' feature in the software ensures the user is notified that at some point an alarm level has been exceeded, without needing to download the data.

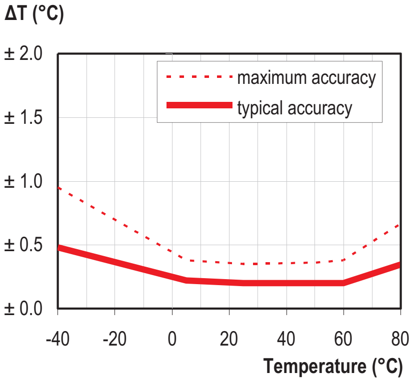
○	**Green double flash** The data logger is not currently logging, but is primed to start at a later date and time (delayed start)
○	**Green single flash** The data logger is currently logging. No alarm on the channel
○	**Red single flash** The data logger is currently logging. Low alarm on the channel
○	**Red double flash** The data logger is currently logging. High alarm on the channel
○	**Green triple flash** The data logger is full and has stopped logging. No alarm on the channel
○	**Red triple flash** The data logger is full and has stopped logging. Alarm (high, low or both) on the channel
○	**No LEDs flash** The data logger is stopped, the battery is empty or there is no battery
○ ○	**Dual Red flash (every 60 seconds)** The data logger battery is running low as it's voltage has dropped below 2.9V

EL-USB-2+

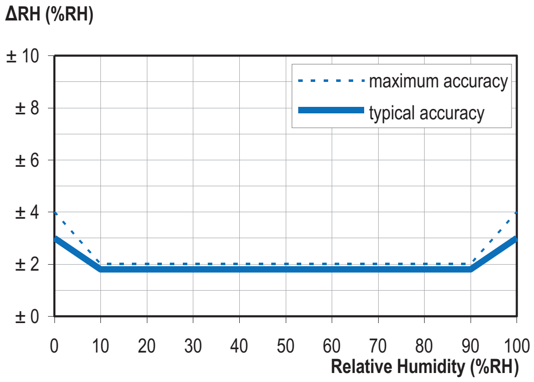
High Accuracy Temperature, Humidity and Dew Point Data Logger

SENSOR ACCURACY & INFORMATION

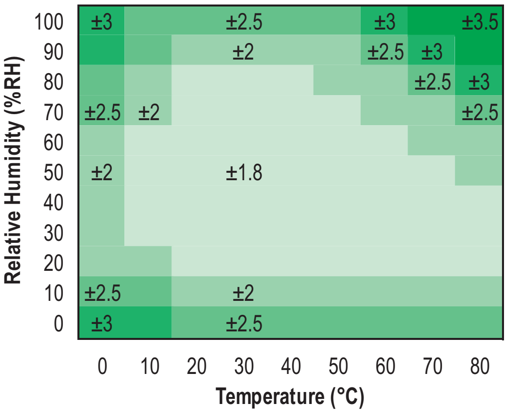
Typical and maximal tolerance for temperature sensor in °C.



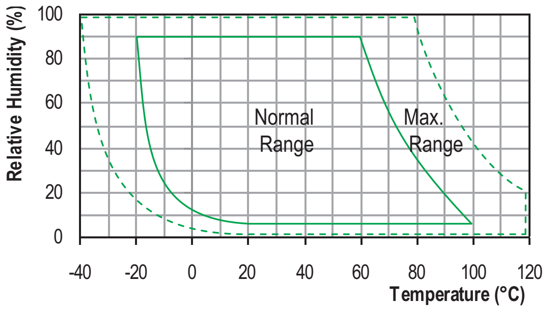
Typical and maximal tolerance at 25°C for relative humidity.



Typical accuracy of relative humidity measurements given in %RH for temperatures 0 to 80°C.



Operating conditions



Long term exposure to humidity levels outside of the 'normal' range may temporarily offset RH measurements (±3%RH after 60 hours). Once returned to less extreme conditions the device will slowly return towards calibration state.

When tracking changes in ambient conditions, the response time of the humidity sensor in your data logger is approximately 20 minutes to reach 90% of the reading. However, if you are measuring step changes in humidity (for example if calibrating the product) it is advised that you leave the unit for up to four hours to ensure that it has enough time to settle at the new level.

It is worth remembering that the value of relative humidity is of course sensitive to temperature variation. As an example, at a relative humidity of ~90%RH at ambient temperature, a variation in temperature of 1°C will result in a change of up to -5%RH. Therefore when comparing multiple devices or calibrating them, any temperature variations must be considered.

EL-USB-2+

High Accuracy Temperature, Humidity and Dew Point Data Logger

SENSOR ACCURACY & INFORMATION

The humidity measuring element in the humidity data loggers can be contaminated through exposure to a variety of compounds. These products should not be kept in proximity to volatile chemicals such as solvents and other organic compounds. Generally speaking, if a material or compound emits a strong odour you should not keep your humidity data logger in close proximity to it. If you would like more information, please contact your local Lascar Electronics office.

Exposure to extreme conditions or chemical vapours will require the following reconditioning procedure to bring the internal sensor back to calibration state:

Baking	80°C (176°F) at < 5%RH for 36 hours.
Re-hydration	20 to 30°C (70 to 90°F) at > 74%RH for 48 hours.

High levels of pollutants may cause permanent damage to the internal sensor.

BATTERY INFORMATION

Replacement

We recommend that you replace the battery annually, or prior to logging critical data. Only use 3.6V ½AA lithium metal batteries. The data logger does not lose its stored readings when the battery is discharged or replaced; however, the data logging process will stop and will not resume until the battery is replaced and the logger restarted by EL-WIN-USB or an EL-DataPad.

Before replacing the battery, remove the data logger from the PC. Please note that leaving the data logger plugged into the USB port for extended periods will cause some of the battery capacity to be lost.

Passivation

If left unused for extended periods of time the lithium metal batteries, including those used in the EasyLog range of data loggers, naturally form a non-conductive internal layer preventing them from self-discharge and effectively increasing their shelf life. When first installed in the data logger, this may cause a momentary drop in the battery voltage (the Transient Minimum Voltage) as the internal layer is broken down, resulting in the data logger resetting. Inserting the batteries in the data logger and leaving it connected to a PC for about 30 seconds will remove this layer. After this, remove and re-install the batteries to reset the data logger. Overall battery life will not be affected.

WARNING

Handle lithium metal batteries carefully, observe warnings on battery casing. Dispose of in accordance with local regulations.

e2 classic

energy monitor and software

efergy

Monitor your home energy use

DOWNLOAD YOUR DATA ★ FOR CLOSER ANALYSIS ★

elink

Download your energy data to for closer analysis

Instantly see the cost of using energy in your home

View your daily, weekly, monthly or average data

Uses multiple tariff options

Discover and reduce your carbon footprint

Learn about energy with your family

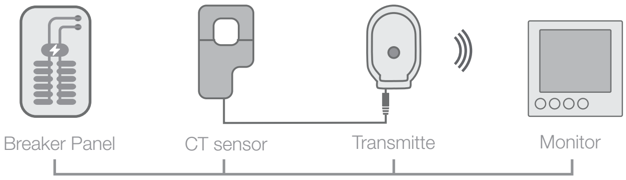
EU UK USA AU

e2 classic

energy monitor and software

efergy®

Our **e2 classic** energy monitor is simple to install and easy to use. The monitor receives data wirelessly via the transmitter and displays the demand in kilowatts of energy being consumed at any given time. The **e2 classic** may be programmed for various rates, ensuring that the cost of your energy is accurate. The **e2 classic** works in conjunction with your energy management software **elink**, which allows you to look at in depth energy information on your computer.



Easy to install

1. Clip the mini CT sensor around the live feed of your electrical panel.

2. Plug the sensor into the transmitter.

3. Press **link** on the back of the **e2 classic** monitor (signal symbol will flash), then press **learn** on the transmitter.

4. Signal symbol becomes solid when the installation is successful. Use the **e2 classic** to review energy usage instantly.

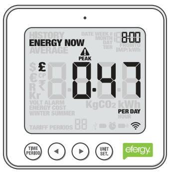
Key features

Download your data

Download your energy consumption data to your PC or Mac and analyse it with our efergy **elink** software. View informative graphs, print or save reports as PDF files. Data may also be viewed using Excel.

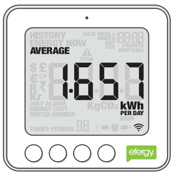
Instant savings

The **e2 classic** shows how much energy is consumed in real-time and how much it will cost if the 'energy now' load is maintained for a period of one day.



Average data

The **e2 classic** displays your average energy usage per day, week and month. See the impact of your energy efficient efforts and then watch your average energy usage reduce.



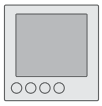
Memory function

The **e2 classic** memory function allows you to view your energy usage by the day, week or month. The **e2 classic** helps you understand your energy usage and how it changes over time.

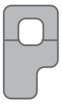
Technical details

Model Name:	e2 classic
Model Number:	E2-3.0
Frequency:	433.5MHz
Transmission Time:	10-15-20s
Transmission Range:	110-600V
Measuring Current:	50mA-90A
Accuracy:	>90%
Dimensions:	86x24x86cm

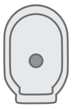
CE RoHS Industry Canada Industrie Canada Canadä Intertek 4000228 FC



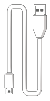
1 x e2 classic



1 x CT sensor (EU)
2 x XL sensor (US/CA)



1 x Transmitter



1 x USB Cable

If you have any question about the **e2 classic**, go to: **engage.efergy.com** or email us at **support@efergy.com**

Sales & Distribution:
Email: sales@efergy.com

www.efergy.com

OWL+USB

SOFTWARE USER GUIDE

Table Of Contents

1.0 INTRODUCTION

Welcome to the OWL+USB Wireless Electricity Monitor that enables data recorded by the monitor to be downloaded and displayed numerically / graphically using the OWL USB Software. Export the data from the database as a .csv file for use in applications such as Excel to manipulate the data or display in other chart formats. Alternatively access the data in the SQLite database using suitable SQLite tools.

How much data can be stored on my OWL+USB?

Data is stored for last 720 days as a daily value of electricity used, cost of electricity used based on Tariff rates entered for that day, and amount of CO2 emissions based on conversion factor for that day. This data is accessible through the History function of the Monitor

Data is also stored every minute for the last 30 days and this is accessed using the automatic download function of the software application supplied with the Monitor.

How much data can I download to my PC from my OWL+USB?

The last 30 days worth of minute by minute data can be downloaded from your OWL+USB.

How do I download the data to my PC?

After installing the software application, having followed the guidelines in the user manual, simply connect the mini-USB port of the monitor to the PC, and the last 30 days data (or number days data stored if less than 30 days) will automatically download to the database on the pc.

How often do I need to download the data to my PC?

Data should be downloaded every 30days since last data download or sooner.

If 30days is exceeded since last download, then the data for the days between the last 30days and last download of data will be overwritten in the monitor, hence there will be no data saved for those days in the database.

Where can the database be found on my PC?

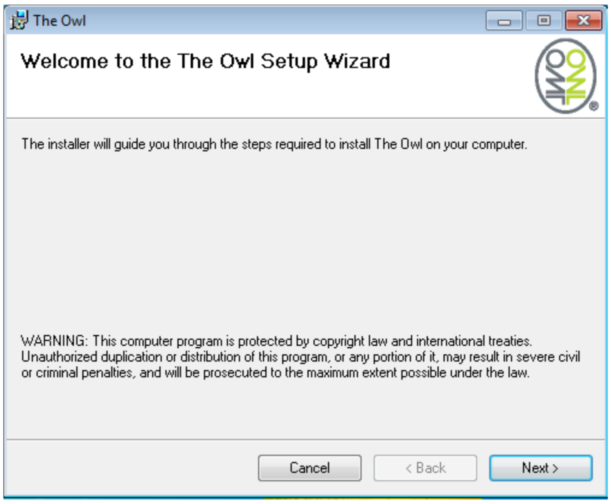
The database file and all exported data files can be found in

Windows XP ➔ “C:\Documents and Settings\All Users\Application Data\2SE”

Windows 7 ➔ “C:\ProgramData\2SE”

2.0 GETTING STARTED

Run the installation program file “**setup_en**” from the CD



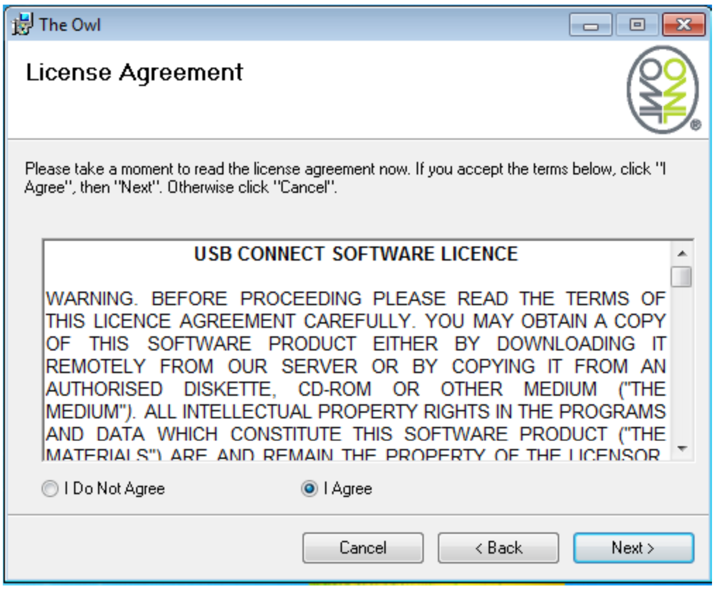
Welcome to the The Owl Setup Wizard

The installer will guide you through the steps required to install The Owl on your computer.

WARNING: This computer program is protected by copyright law and international treaties. Unauthorized duplication or distribution of this program, or any portion of it, may result in severe civil or criminal penalties, and will be prosecuted to the maximum extent possible under the law.

Proceed to the License Agreement Acceptance by pressing the [Next>] key.

2.2.1 License Agreement



License Agreement

Please take a moment to read the license agreement now. If you accept the terms below, click "I Agree", then "Next". Otherwise click "Cancel".

USB CONNECT SOFTWARE LICENCE

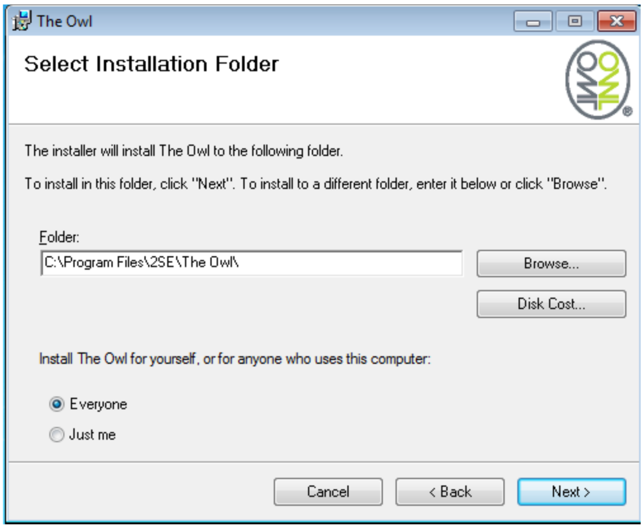
WARNING. BEFORE PROCEEDING PLEASE READ THE TERMS OF THIS LICENCE AGREEMENT CAREFULLY. YOU MAY OBTAIN A COPY OF THIS SOFTWARE PRODUCT EITHER BY DOWNLOADING IT REMOTELY FROM OUR SERVER OR BY COPYING IT FROM AN AUTHORISED DISKETTE, CD-ROM OR OTHER MEDIUM ("THE MEDIUM"). ALL INTELLECTUAL PROPERTY RIGHTS IN THE PROGRAMS AND DATA WHICH CONSTITUTE THIS SOFTWARE PRODUCT ("THE MATERIALS") ARE AND REMAIN THE PROPERTY OF THE LICENSOR

○ I Do Not Agree ● I Agree

Select “I Agree” and press [Next>] to move to next stage of installation
A copy of the License Agreement is available on the CD

2.2.2 Software Installation

The installation of the OWL Home Energy Monitor program will default to “C:\Program Files\2SE\The Owl\”.



The Owl

Select Installation Folder

The installer will install The Owl to the following folder.

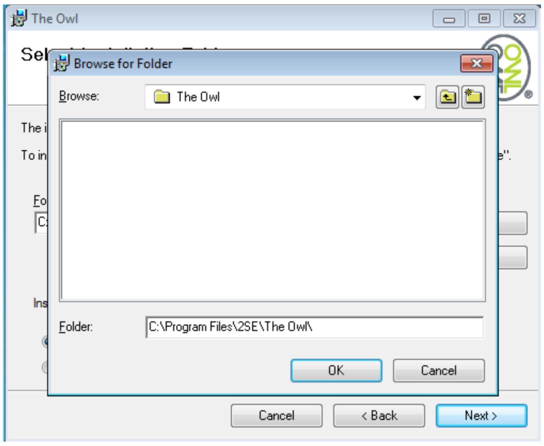
To install in this folder, click "Next". To install to a different folder, enter it below or click "Browse".

Folder: C:\Program Files\2SE\The Owl\

Install The Owl for yourself, or for anyone who uses this computer:

● Everyone
○ Just me

A different folder location can be used to install The OWL Home Energy Monitor application by selecting the [Browse…] button.
Check to see which disk has enough room to load the program using the [Disk Cost…] button

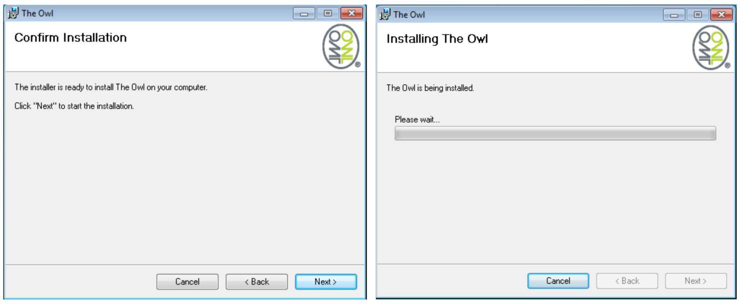


Browse for Folder

Browse: The Owl

Folder: C:\Program Files\2SE\The Owl\

Confirm that you are ready to proceed with the installation by selecting [Next>] button.



Confirm Installation

The installer is ready to install The Owl on your computer.

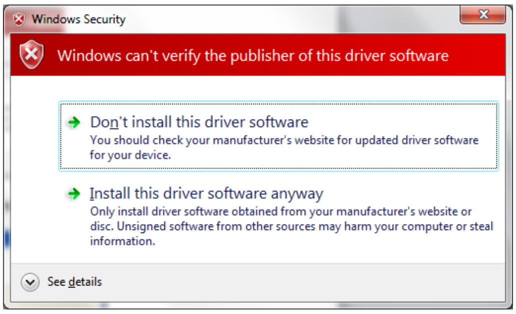
Click "Next" to start the installation.

Installing The Owl

The Owl is being installed.

Please wait...

The Owl Home Energy Monitor software is being installed.

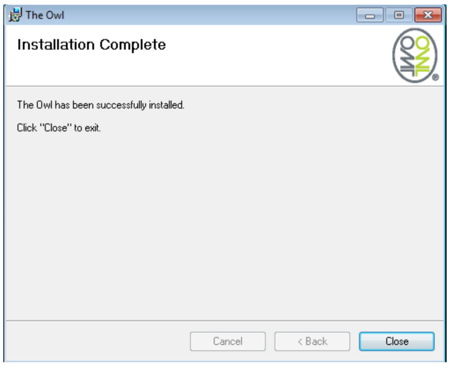


Windows can't verify the publisher of this driver software

Don't install this driver software
You should check your manufacturer's website for updated driver software for your device.

Install this driver software anyway
Only install driver software obtained from your manufacturer's website or disc. Unsigned software from other sources may harm your computer or steal information.

Select Install this driver anyway.

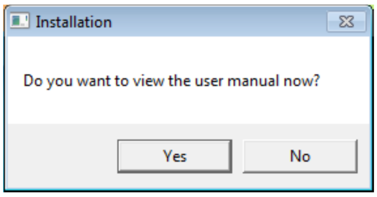


Installation Complete

The Owl has been successfully installed.

Click "Close" to exit.

The OWL Home Energy Monitor has been successfully installed. To exit from the installation select the [Close] button.



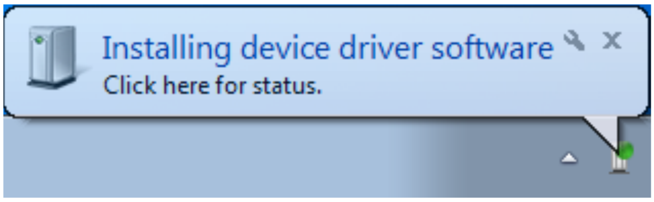
Do you want to view the user manual now?

Electronic version of the manual is offered at the end of the procedure.

3.0 CONNECTING THE MONITOR

Do not start The_Owl software yet.

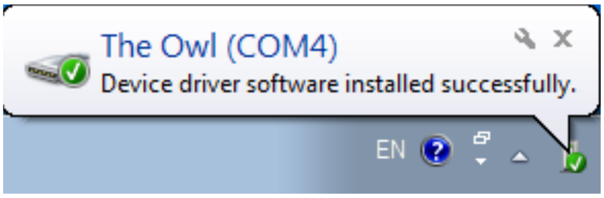
Next connect your OWL Monitor to the PC using the micro USB cable supplied.



Installing device driver software

Click here for status.

Notification that the device drivers are being installed will show.



The Owl (COM4)

Device driver software installed successfully.

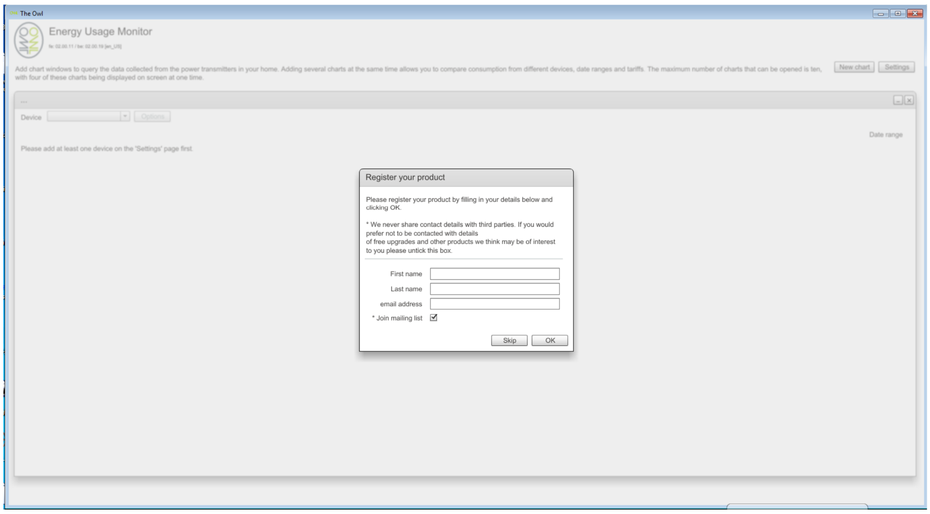
When installation is complete you will receive a successfully installed message

4.0 USING YOUR OWL+USB

Go to START > Menu > All Programs > The Owl > The Owl and select.

3.1 PRODUCT REGISTRATION

Product registration is required to validate your product guarantee and to inform you via e-mail of any software updates that will be accessible as a download from the website. You can choose to skip registration but will be requested each time you open the program to register the product.



Add chart windows to query the data collected from the power transmitters in your home. Adding several charts at the same time allows you to compare consumption from different devices, date ranges and tariffs. The maximum number of charts that can be opened is ten, with four of these charts being displayed on screen at one time.

Please add at least one device on the 'Settings' page first.

Please register your product by filling in your details below and clicking OK.

* We never share contact details with third parties. If you would prefer not to be contacted with details of free upgrades and other products we think may be of interest to you please untick this box.

* Un-check the box if you do not wish to be added to our Newsletter mailing list where you will receive information about new product releases and promotions.

3.2 SETTINGS –

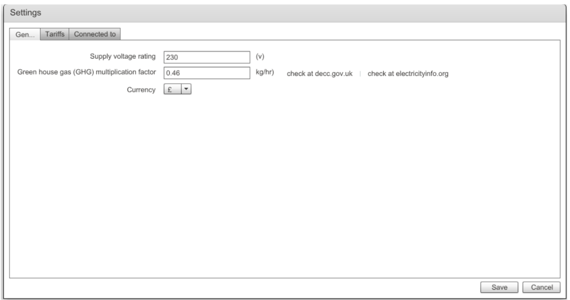
Settings for the OWL+USB are taken from the figures input into the monitor.
See the Quick Start Guide for instructions.
Information below can be used as a guide for setting up alternate tariffs for comparison charts.
The USB Connect requires input of currency, voltage, GHG and Tariff settings as below.

Before connecting your USB CONNECT to your PC for the first time you will need to setup your currency, voltage & GHG settings as per the settings in your OWL+USB, so that when the OWL+USB is connected to the PC downloading data or getting live data, it will use these settings for any calculations and update the database with these values.

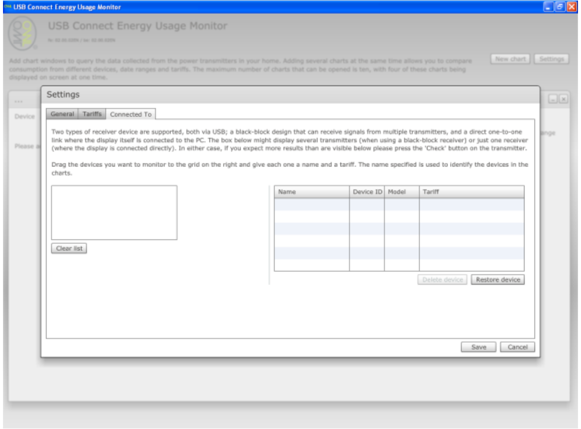
If using for the first time, follow the instructions in section “3.2.1 General”, save your settings minimise the OWL Connect window and move to step 3.2.3

Select the settings button and the settings screen is split into 3 tabs:-

- General
  - For setting up the voltage, greenhouse conversion factor, and currency.
  - Links to related websites that could help you finding out the conversion factor relating to your utility company.
- Tariffs
  - Tariff values are determined from the downloaded data from the OWL+USB
  - Set up other cost of electricity plans that can be used when using Tariff Comparison



Supply voltage rating 230 (v)
Green house gas (GHG) multiplication factor 0.46 kg/hr) check at decc.gov.uk | check at electricityinfo.org
Currency £



Add chart windows to query the data collected from the power transmitters in your home. Adding several charts at the same time allows you to compare consumption from different devices, date ranges and tariffs. The maximum number of charts that can be opened is ten, with four of these charts being displayed on screen at one time.

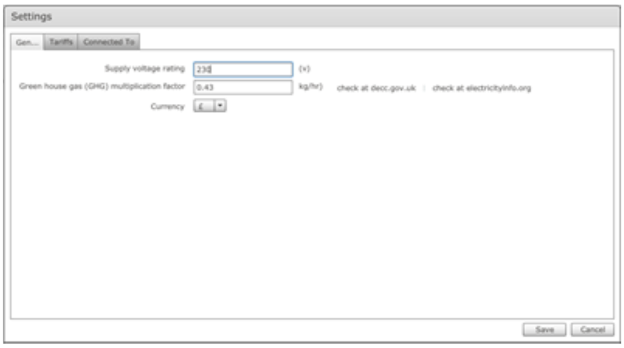
Two types of receiver device are supported, both via USB; a black-block design that can receive signals from multiple transmitters, and a direct one-to-one link where the display itself is connected to the PC. The box below might display several transmitters (when using a black-block receiver) or just one receiver (where the display is connected directly). In either case, if you expect more results than are visible below please press the 'Check' button on the transmitter.

Drag the devices you want to monitor to the grid on the right and give each one a name and a tariff. The name specified is used to identify the devices in the charts.

Name	Device ID	Model	Tariff

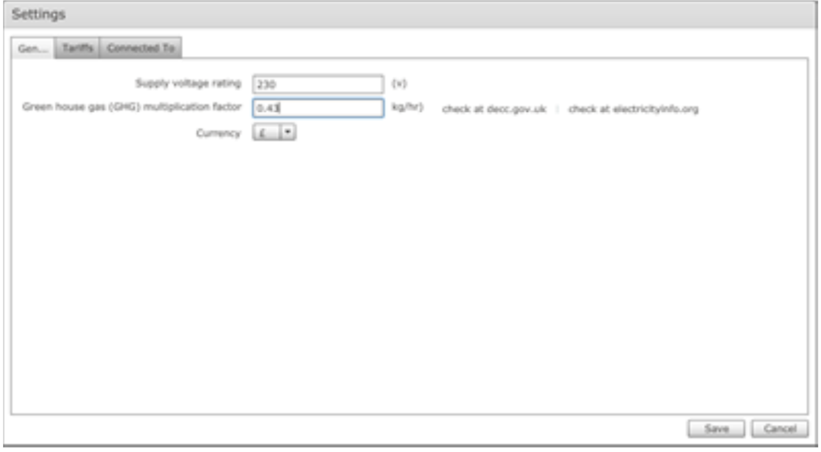
3.2.1 General

To change the Supply Voltage rating place cursor over the current value and select. The box will be highlighted by a blue line around the edge of the Supply Voltage rating box. Change the value and press the [Enter] key.



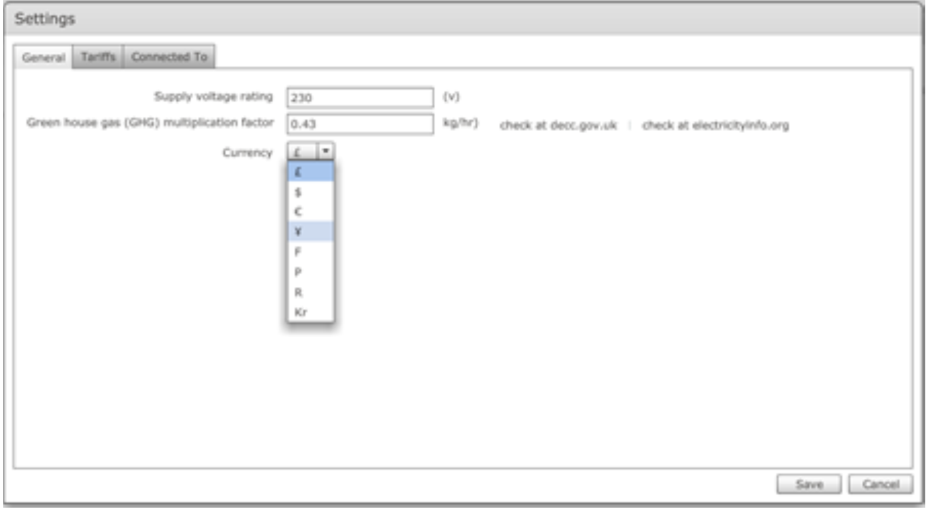
Supply voltage rating 230 (v)
Green house gas (GHG) multiplication factor 0.43 kg/hr)
Currency £

To change the Greenhouse gas multiplication factor place cursor over the current value and select. The box will be highlighted by a blue line around the edge of the Greenhouse gas multiplication factor box. Change the value and press the [Enter] key.



Supply voltage rating 230 (v)
Green house gas (GHG) multiplication factor 0.43 kg/hr)
Currency £

For greenhouse multiplication or conversion factors use the links to take you to related websites that could help you with finding out the multiplication or conversion factor relating to your utility company.



Supply voltage rating 230 (v)
Green house gas (GHG) multiplication factor 0.43 kg/hr)
Currency £

Use the pull down menu to select currency setting.

3.2.2 Tariffs

A nominal tariff has been preset within the software but this can be changed or removed as required. Cost per kWh are in sub-units ie pence / cents, so for a Cost per kWh of £2-845 the value to be entered would be 284-50

For Tariff plans that only have a single band then start time should be left set at 0:00.

To introduce tariff plans for comparison purposes select the [Add] key.

Add your current energy tariff and any other tariffs you are interested in below. Each device has a default tariff that is used to store the cost of past energy consumption. Using the charts you can make tariff comparisons.

Name
Standard
[Enter name here]

	Cost/kWh	Start Time	Mon-Sun	Mon-Fri	Sat-Sun
☑ Tariff 1	10.50	00:00	●	○	○
☐ Tariff 2		00:00	○	○	○
☐ Tariff 3		00:00	○	○	○
☐ Tariff 4		00:00	○	○	○
☐ Tariff 5		00:00	○	○	○
☐ Tariff 6		00:00	○	○	○

To edit the tariff name, rates, and start times applied to weekly, weekday only, or weekend only rate, select the tariff name [Enter name here].

Add your current energy tariff and any other tariffs you are interested in below. Each device has a default tariff that is used to store the cost of past energy consumption. Using the charts you can make tariff comparisons.

Name
Standard
Enter name here

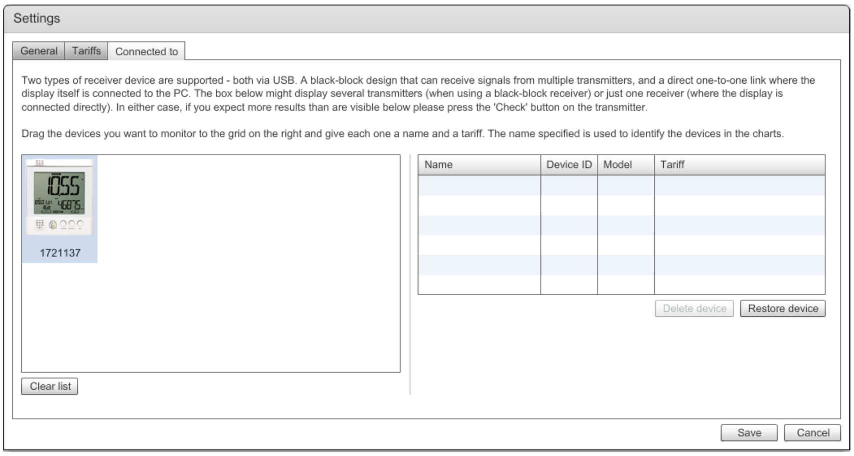
	Cost/kWh	Start Time	Mon-Sun	Mon-Fri	Sat-Sun
☑ Tariff 1	0.00	00:00	●	○	○
☑ Tariff 2	0.00	00:00	●	○	○
☑ Tariff 3	0.00	00:00	●	○	○
☑ Tariff 4	0.00	00:00	●	○	○
☑ Tariff 5	0.00	00:00	●	○	○
☑ Tariff 6	0.00	00:00	●	○	○

Enter a name for the new tariff. All six possible tariff rates/start times will be checked. Uncheck those not required

Repeat as required for other Tariff plans.

3.2.3 Connected To – Both USB CONNECT and OWL+USB

Add the unit to the Connected to window.
Up to five OWL+USBs can be connected to the PC at the same time. There is no limit set on the number of OWL+USBs the software will add to the database.
Note it may take a little time for the USB display to appear in the window.



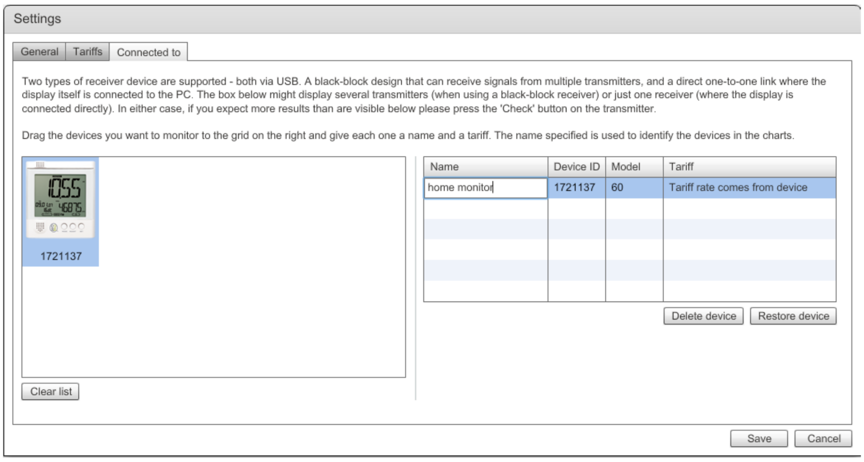
Two types of receiver device are supported - both via USB. A black-block design that can receive signals from multiple transmitters, and a direct one-to-one link where the display itself is connected to the PC. The box below might display several transmitters (when using a black-block receiver) or just one receiver (where the display is connected directly). In either case, if you expect more results than are visible below please press the 'Check' button on the transmitter.

Drag the devices you want to monitor to the grid on the right and give each one a name and a tariff. The name specified is used to identify the devices in the charts.

Name	Device ID	Model	Tariff

Drag and drop the USB from the Sensors window into the device table.

Insert a name to identify the USB.
The tariff values will be determined from the OWL+USB data.
Try not to use punctuation in the device name as this can cause problems with the database on some PCs.



Two types of receiver device are supported - both via USB. A black-block design that can receive signals from multiple transmitters, and a direct one-to-one link where the display itself is connected to the PC. The box below might display several transmitters (when using a black-block receiver) or just one receiver (where the display is connected directly). In either case, if you expect more results than are visible below please press the 'Check' button on the transmitter.

Drag the devices you want to monitor to the grid on the right and give each one a name and a tariff. The name specified is used to identify the devices in the charts.

Name	Device ID	Model	Tariff
home monitor	1721137	60	Tariff rate comes from device

Save settings by selecting <Save> button or select <Cancel> button to leave settings window without saving any of these changes.

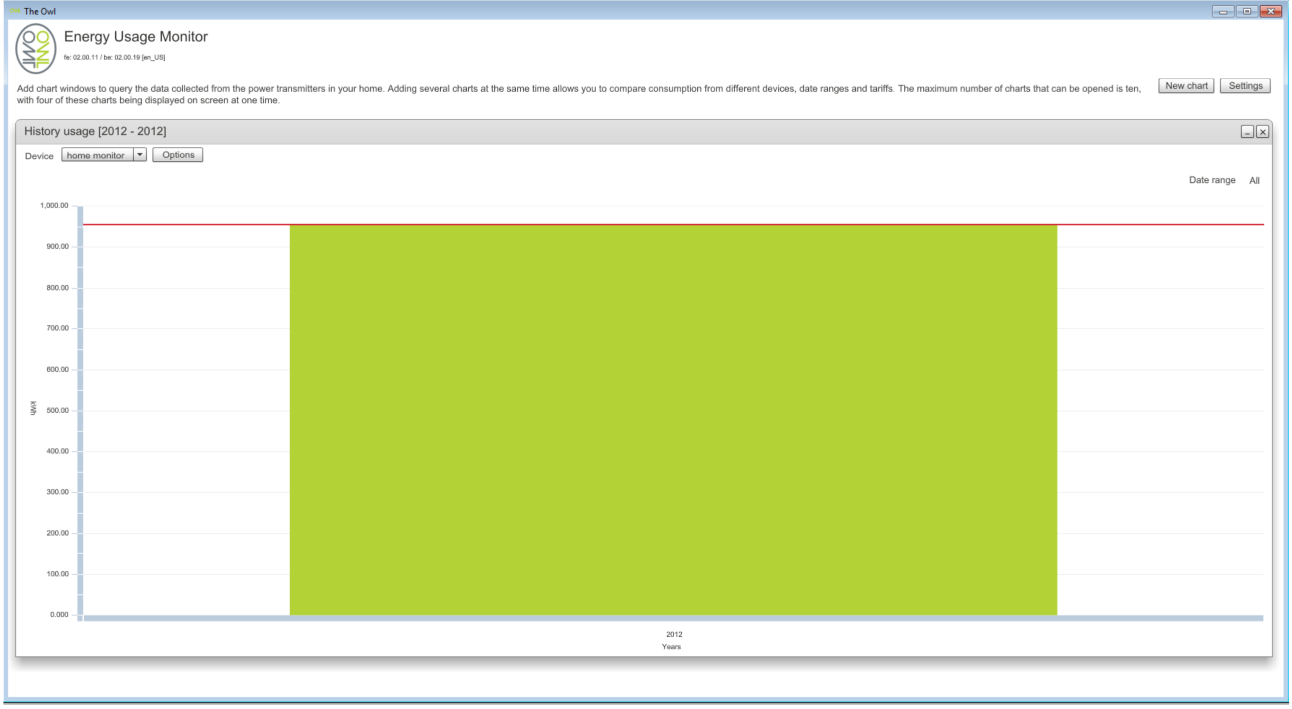
5.0 VIEWING THE DATA

After leaving the settings page for the first time, there may be a slight delay in a history chart appearing for the first transmitter in your list until sufficient data has been added to the database.
Navigate through the chart options using the different option through the <Options> button.

- View “Live” Data as a cost, as kW & CO2 emissions using line charts / bar charts / numeric display.
- View “Historical” Data as an accumulated cost, as accumulated kWh & accumulated CO2 emissions using line charts / bar charts / numeric display.
    - Review data down to a per minute usage by clicking on the data point/bar
- View data point values by passing cursor over the data point/bar
- Maximum / Minimum markers
- Compare tariffs
- Open multiple charts (10) with a maximum of 4 being displayed at any one time
- Export raw data from database into a .csv file for use with spreadsheet packages such as Excel.
    - Live display ➔ Exports Data Displayed (Last 2 Minutes)
    - Historic Display ➔ Exports Data Displayed (Years, Months, Days, Hours, Minutes)
    - Historic Display ➔ Exports Data between 2 dates based on chart time base (ie Day will export Daily Data between 2 dates)
    - Historic Display ➔ Exports All Data
- Simple printout of the chart displayed

4.1 ADDING CHARTS

Up to 10 charts can be open at one time and are added using the <New Chart> button.



Energy Usage Monitor

fe: 02.00.11 / be: 02.00.19 [en_US]

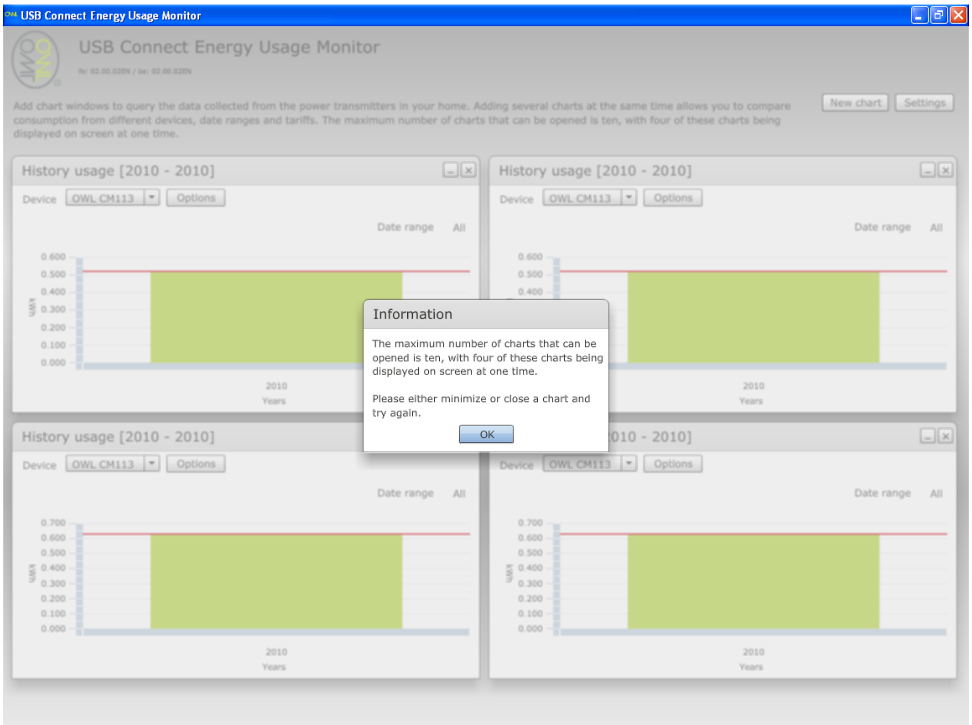
Add chart windows to query the data collected from the power transmitters in your home. Adding several charts at the same time allows you to compare consumption from different devices, date ranges and tariffs. The maximum number of charts that can be opened is ten, with four of these charts being displayed on screen at one time.

History usage [2012 - 2012]

Device: home monitor

Date range: All

If 4 charts are already being display on the screen, one of these will need to be minimised to allow the next chart to be added.



USB Connect Energy Usage Monitor

Add chart windows to query the data collected from the power transmitters in your home. Adding several charts at the same time allows you to compare consumption from different devices, date ranges and tariffs. The maximum number of charts that can be opened is ten, with four of these charts being displayed on screen at one time.

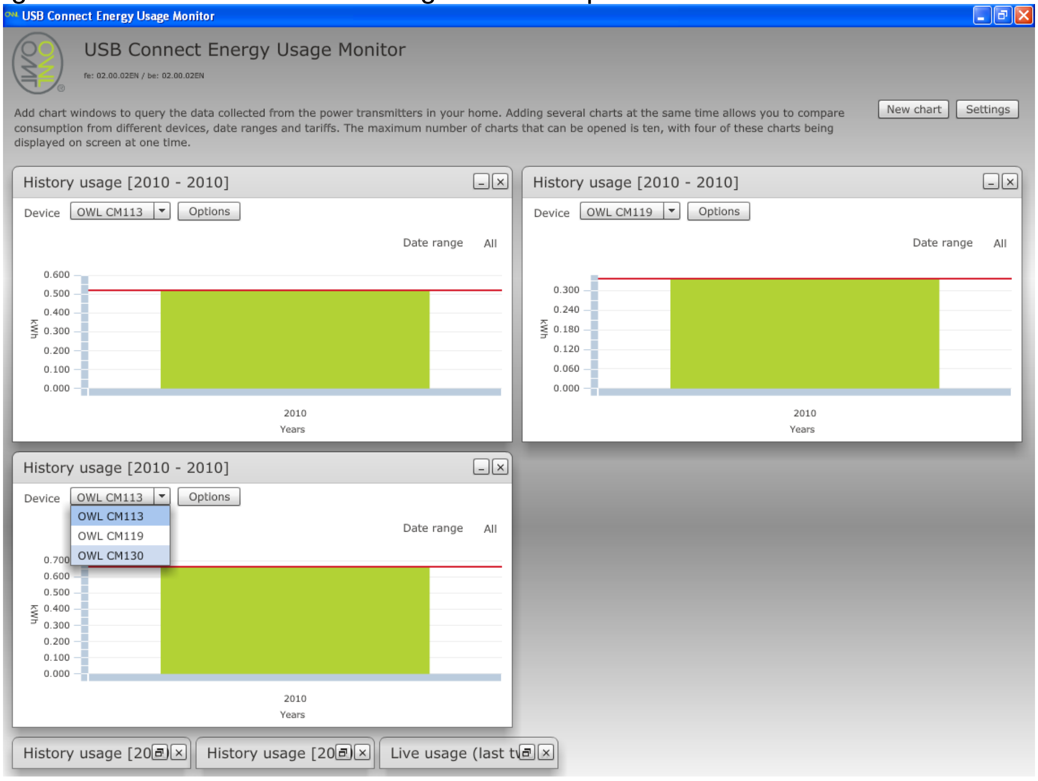
Information

The maximum number of charts that can be opened is ten, with four of these charts being displayed on screen at one time.

Please either minimize or close a chart and try again.

OK

Applying charts to devices is done using the device pull down menu

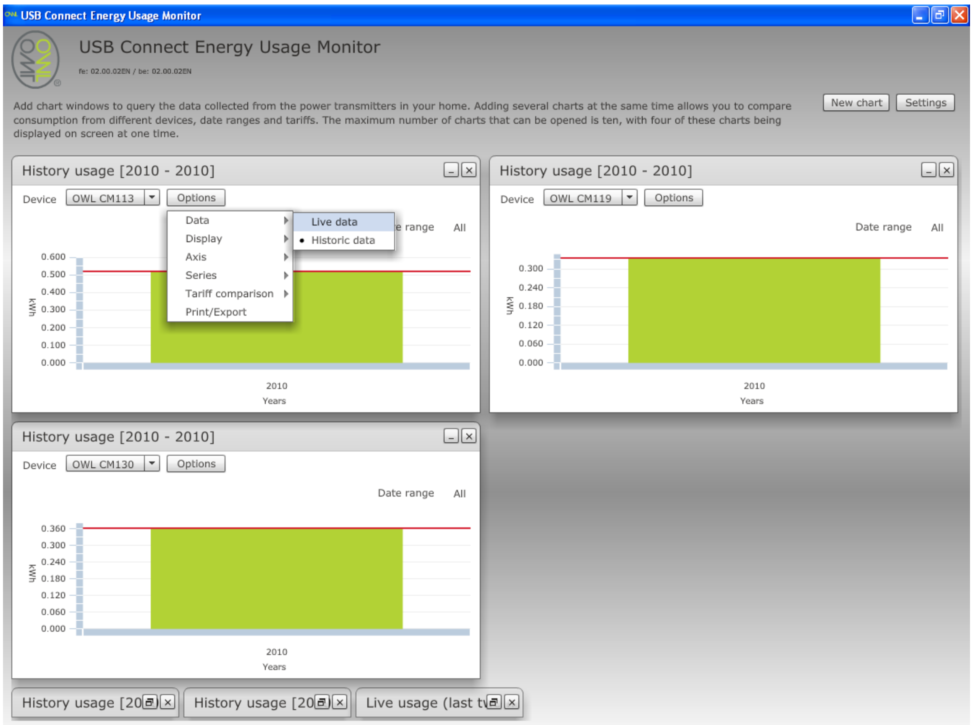


USB Connect Energy Usage Monitor

Add chart windows to query the data collected from the power transmitters in your home. Adding several charts at the same time allows you to compare consumption from different devices, date ranges and tariffs. The maximum number of charts that can be opened is ten, with four of these charts being displayed on screen at one time.

4.2 LIVE DATA CHARTS

See the electricity as it is being consumed displayed in chart form showing it as cost, power and CO2 emissions.

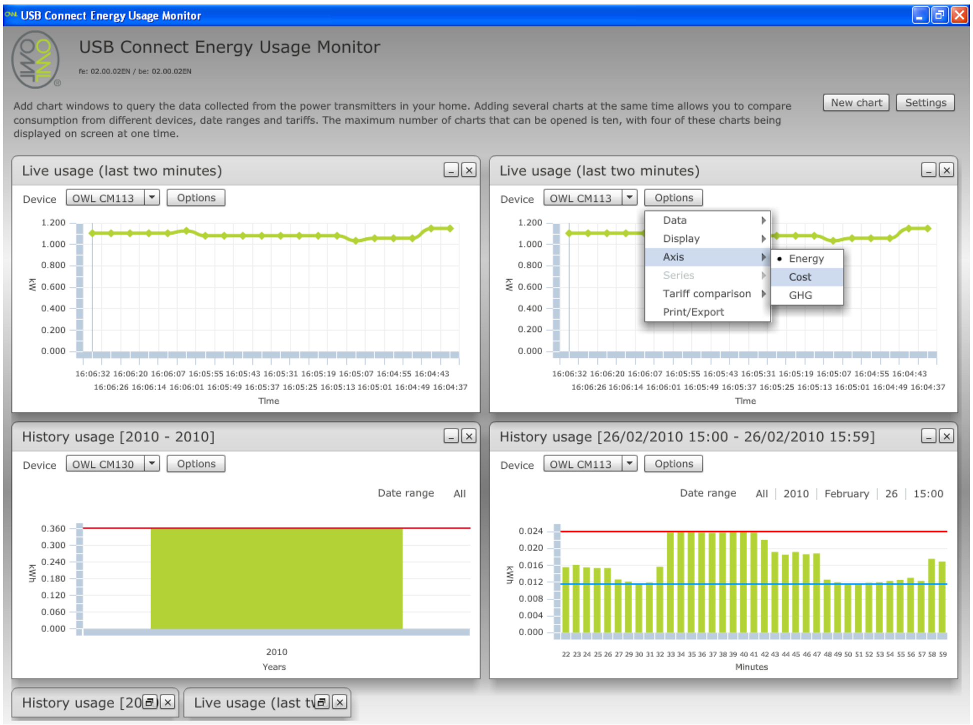


USB Connect Energy Usage Monitor

fe: 02.00.02EN / be: 02.00.02EN

Add chart windows to query the data collected from the power transmitters in your home. Adding several charts at the same time allows you to compare consumption from different devices, date ranges and tariffs. The maximum number of charts that can be opened is ten, with four of these charts being displayed on screen at one time.

- Energy Chart ➔ Shows the electricity in use in kW, calculated from the voltage setting you have used within the settings page and the electrical current reported by the sensor.

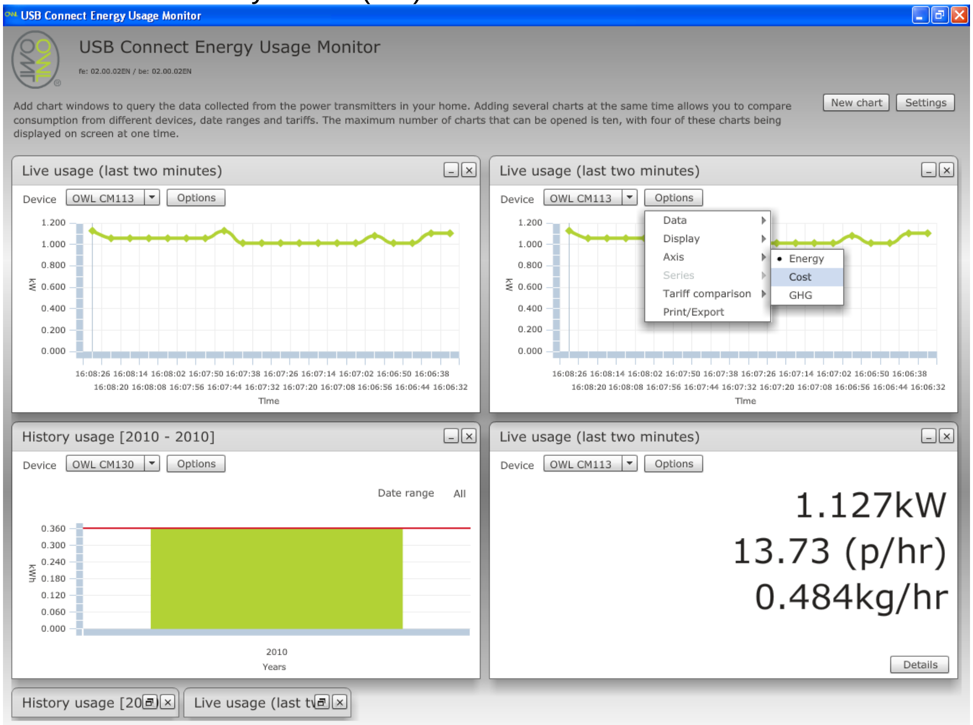


USB Connect Energy Usage Monitor

fe: 02.00.02EN / be: 02.00.02EN

Add chart windows to query the data collected from the power transmitters in your home. Adding several charts at the same time allows you to compare consumption from different devices, date ranges and tariffs. The maximum number of charts that can be opened is ten, with four of these charts being displayed on screen at one time.

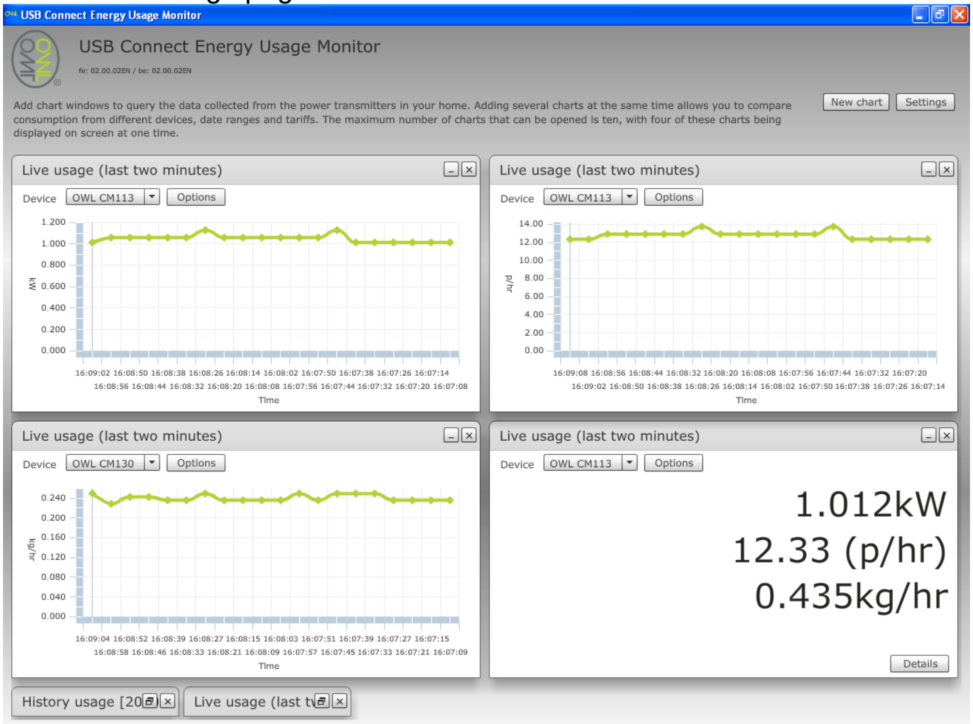
- Cost Chart➔ Shows the cost of electricity as it is being used, calculated from the tariff setting you have set up for the sensor within the settings page and the calculated electricity in use (kW).



Add chart windows to query the data collected from the power transmitters in your home. Adding several charts at the same time allows you to compare consumption from different devices, date ranges and tariffs. The maximum number of charts that can be opened is ten, with four of these charts being displayed on screen at one time.

1.127kW
13.73 (p/hr)
0.484kg/hr

- GHG Chart➔ Shows the calculated CO2 emissions for generating the electricity you are currently using based upon the GHG Conversion Factor you have used within the settings page.



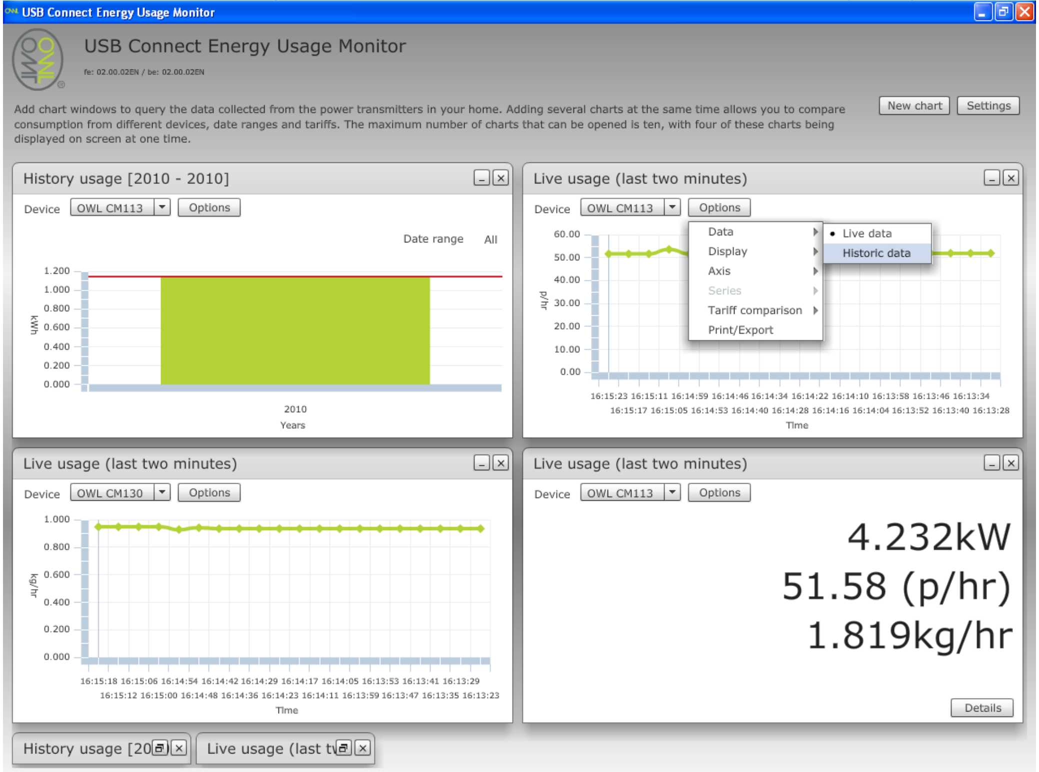
Add chart windows to query the data collected from the power transmitters in your home. Adding several charts at the same time allows you to compare consumption from different devices, date ranges and tariffs. The maximum number of charts that can be opened is ten, with four of these charts being displayed on screen at one time.

1.012kW
12.33 (p/hr)
0.435kg/hr

- Numeric ➔ Shows the live data of the electricity in use in kW, as a cost, and shows CO2 emissions.

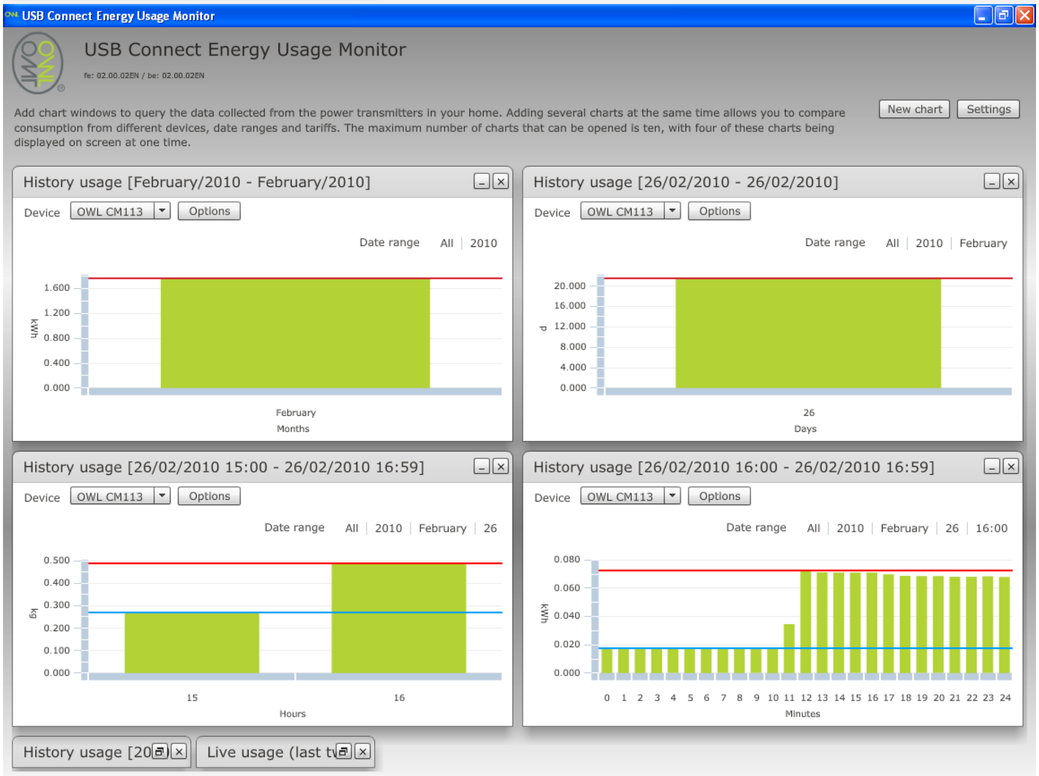
4.3 HISTORICAL DATA CHARTS

This will take you into the top level of the data shown as data used on a yearly timeline.



Add chart windows to query the data collected from the power transmitters in your home. Adding several charts at the same time allows you to compare consumption from different devices, date ranges and tariffs. The maximum number of charts that can be opened is ten, with four of these charts being displayed on screen at one time.

4.232kW
51.58 (p/hr)
1.819kg/hr

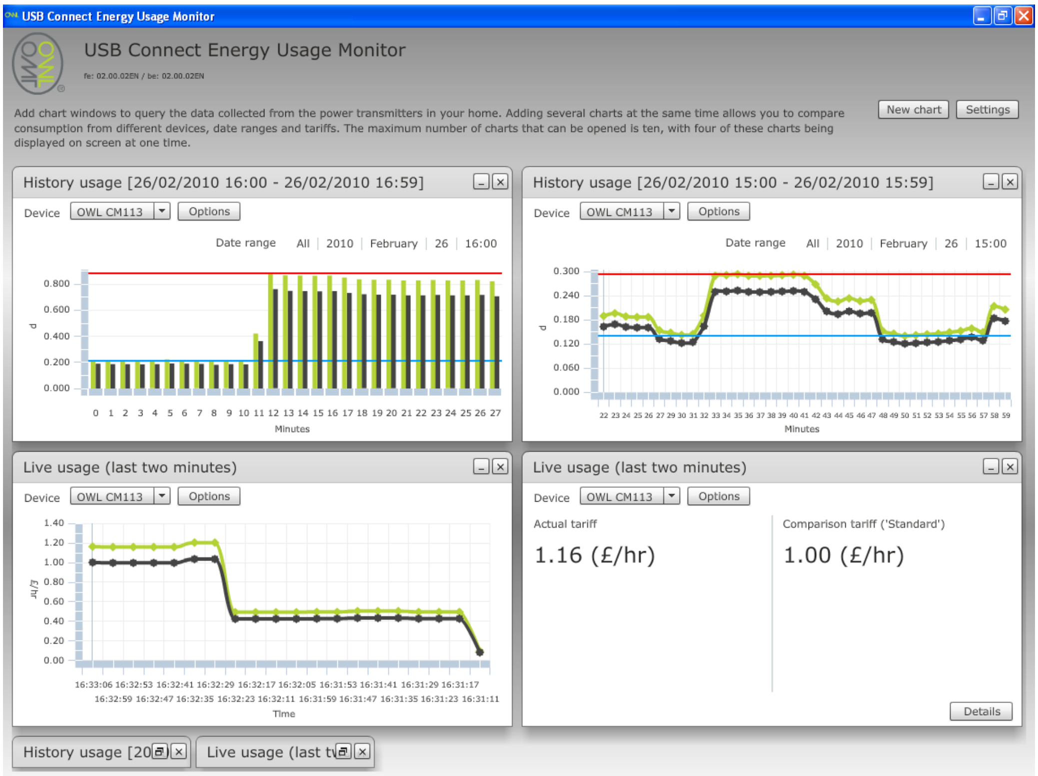


Add chart windows to query the data collected from the power transmitters in your home. Adding several charts at the same time allows you to compare consumption from different devices, date ranges and tariffs. The maximum number of charts that can be opened is ten, with four of these charts being displayed on screen at one time.

Drill down into the data by placing the cursor over the data bar you want to look at in more detail, select that the data bar by double clicking your mouse key to then see the data on a monthly basis. To view on a daily, hourly and per minute repeat steps above.

4.4 TARIFF COMPARISON

Comparing tariff plans using Live data or Historical data against other entered tariff plans.



USB Connect Energy Usage Monitor

fe: 02.00.02EN / be: 02.00.02EN

Add chart windows to query the data collected from the power transmitters in your home. Adding several charts at the same time allows you to compare consumption from different devices, date ranges and tariffs. The maximum number of charts that can be opened is ten, with four of these charts being displayed on screen at one time.

Actual tariff: 1.16 (£/hr)

Comparison tariff ('Standard'): 1.00 (£/hr)

6.0 EXPORTING DATA

Exported data is saved to a default folder **"C:\Documents and Settings\All Users.WINDOWS\Application Data\2SE"** and the filename is generated from device name and date/time saved.
A shortcut to this folder can be found Start>Programs>OWL USB Connect 2.
After exporting a file the OWL USB Connect 2 user interface will be minimised and the OWL Data folder opened on the screen.
The exported data is downloaded in columns under the following headings:-

Sensor	Sensor identification associated with exported data.
Time	Timestamp of when data was recorded.
GHG Factor	GHG Factor applied to recorded data
Tariff Cost	Tariff Rate applied to recorded data.
Amps_Raw_Data	Raw data value relating to Amps measured by the sensor during that time period.
Amps_Raw_Data_Min	Minimum raw data value relating to Amps measured by the sensor during that time period (ie Minimum value during that Day, Hour, Minute)
Amps_Raw_Data_Max	Maximum raw data value of Amps measured by the sensor during that time base (ie Minimum value during that Day, Hour, Minute)
kW_Raw_Data	Raw data value of kW calculated using Amps_Raw_Data and the voltage applied in the settings window when data was recorded.
kW_Raw_Data_Min	Minimum raw data value of kW calculated using Amps_Raw_Data_Min and the voltage applied in the settings window when data was recorded.
kW_Raw_Data_Max	Maximum raw data value of kW calculated using Amps_Raw_Data_Max and the voltage applied in the settings window when data was recorded.
Cost_Raw_Data	Raw data value of cost of electricity using applied tariff during the period between this and previous time stamp.
Cost _Raw_Data_Min	Minimum raw data value of cost of electricity using applied tariff during the period between this and previous time stamp.
Cost_Raw_Data_Max	Maximum raw data value of cost of electricity using applied tariff during the period between this and previous time stamp.
GHG_Raw_Data	Raw data value of calculated weight of Carbon Dioxide emissions using applied conversion factor during the period between this and previous time stamp.
GHG_Raw_Data_Min	Raw data value of calculated weight of Carbon Dioxide emissions using applied conversion factor during the period between this and previous time stamp.
GHG_Raw_Data_Max	Raw data value of calculated weight of Carbon Dioxide emissions using applied conversion factor during the period between this and previous time stamp.

5.1 HOW TO CONVERT EXPORTED RAW DATA?

Take the raw data and using the calculations below, convert the Current, Energy, Cost & GHG data columns.

- Current (Amps) ➔ Amps Value x 60
  - ie: 0.05 x 60 = 3 Amps
- Energy (kW) ➔ kW value ÷ 1,000
  - ie: 4.4 ÷ 1,000 = 0.0044kW (or 4.4W)
- Cost (pence or cents) ➔ Cost value ÷ 100,000
  - ie: 520000 ÷ 100,000, = 5.2pence
- GHG (kg) ➔ GHG value ÷ 100,000
  - ie: 7100 ÷ 100,000 = 0.071kg (or 71g)

5.2 EXPORTING LIVE CHART DATA

Using the export function when viewing live data will download the current data as shown in the 2 minute live usage chart.

Device	Time	GHG_Factor	Tariff_Cost	Amps_Raw_Data	Amps_Raw_Data_Min	Amps_Raw_Data_Max	kW_Raw_Data	kW_Raw_Data_Min	kW_Raw_Data_Max	Cost_Raw_Data	Cost_Raw_Data_Min	Cost_Raw_Data_Max	GHG_Raw_Data	GHG_Raw_Data_Min
OWL CM113	08:48:04	0.43	12.19	3.1	2.8	28	713	644	6440	869147	785036	7850360	30659	27692
OWL CM113	08:47:58	0.43	12.19	2.9	2.8	28	667	644	6440	813073	785036	7850360	28681	27692
OWL CM113	08:47:52	0.43	12.19	2.9	2.8	28	667	644	6440	813073	785036	7850360	28681	27692
OWL CM113	08:47:46	0.43	12.19	2.9	2.8	28	667	644	6440	813073	785036	7850360	28681	27692
OWL CM113	08:47:40	0.43	12.19	2.9	2.8	28	667	644	6440	813073	785036	7850360	28681	27692
OWL CM113	08:47:34	0.43	12.19	2.9	2.8	28	667	644	6440	813073	785036	7850360	28681	27692
OWL CM113	08:47:28	0.43	12.19	2.9	2.8	28	667	644	6440	813073	785036	7850360	28681	27692
OWL CM113	08:47:22	0.43	12.19	2.9	2.8	28	667	644	6440	813073	785036	7850360	28681	27692
OWL CM113	08:47:16	0.43	12.19	2.9	2.8	28	667	644	6440	813073	785036	7850360	28681	27692
OWL CM113	08:47:10	0.43	12.19	2.9	2.8	28	667	644	6440	813073	785036	7850360	28681	27692
OWL CM113	08:47:04	0.43	12.19	2.9	2.8	28	667	644	6440	813073	785036	7850360	28681	27692
OWL CM113	08:46:58	0.43	12.19	3.2	2.8	28	736	644	6440	897184	785036	7850360	31648	27692
OWL CM113	08:46:52	0.43	12.19	3.2	2.8	28	736	644	6440	897184	785036	7850360	31648	27692
OWL CM113	08:46:46	0.43	12.19	3.2	2.8	28	736	644	6440	897184	785036	7850360	31648	27692
OWL CM113	08:46:40	0.43	12.19	3.2	2.8	28	736	644	6440	897184	785036	7850360	31648	27692
OWL CM113	08:46:34	0.43	12.19	3.2	2.8	28	736	644	6440	897184	785036	7850360	31648	27692
OWL CM113	08:46:28	0.43	12.19	2.9	2.8	28	667	644	6440	813073	785036	7850360	28681	27692
OWL CM113	08:46:22	0.43	12.19	2.9	2.8	28	667	644	6440	813073	785036	7850360	28681	27692
OWL CM113	08:46:16	0.43	12.19	2.9	2.8	28	667	644	6440	813073	785036	7850360	28681	27692
OWL CM113	08:46:10	0.43	12.19	3.2	2.8	28	736	644	6440	897184	785036	7850360	31648	27692

Converted data shown below:-

Device	Time	GHG_Factor	Tariff_Cost	Amps_Conv_Data (A)	Amps_Conv_Data_Min (A)	Amps_Conv_Data_Max (A)	kW_Conv_Data (kW)	kW_Conv_Data_Min (kW)	kW_Conv_Data_Max (kW)	Cost_Conv_Data (p/c)	Cost_Conv_Data_Min (p/c)	Cost_Conv_Data_Max (p/c)	GHG_Conv_Data (kg)	GHG_Conv_Data_Min (kg)
OWL CM113	08:48:04	0.43	12.19	3.1	2.8	28	0.00713	0.00644	0.0644	8.69147	7.85036	78.5036	0.30659	0.27692
OWL CM113	08:47:58	0.43	12.19	2.9	2.8	28	0.00667	0.00644	0.0644	8.13073	7.85036	78.5036	0.28681	0.27692
OWL CM113	08:47:52	0.43	12.19	2.9	2.8	28	0.00667	0.00644	0.0644	8.13073	7.85036	78.5036	0.28681	0.27692
OWL CM113	08:47:46	0.43	12.19	2.9	2.8	28	0.00667	0.00644	0.0644	8.13073	7.85036	78.5036	0.28681	0.27692
OWL CM113	08:47:40	0.43	12.19	2.9	2.8	28	0.00667	0.00644	0.0644	8.13073	7.85036	78.5036	0.28681	0.27692
OWL CM113	08:47:34	0.43	12.19	2.9	2.8	28	0.00667	0.00644	0.0644	8.13073	7.85036	78.5036	0.28681	0.27692
OWL CM113	08:47:28	0.43	12.19	2.9	2.8	28	0.00667	0.00644	0.0644	8.13073	7.85036	78.5036	0.28681	0.27692
OWL CM113	08:47:22	0.43	12.19	2.9	2.8	28	0.00667	0.00644	0.0644	8.13073	7.85036	78.5036	0.28681	0.27692
OWL CM113	08:47:16	0.43	12.19	2.9	2.8	28	0.00667	0.00644	0.0644	8.13073	7.85036	78.5036	0.28681	0.27692
OWL CM113	08:47:10	0.43	12.19	2.9	2.8	28	0.00667	0.00644	0.0644	8.13073	7.85036	78.5036	0.28681	0.27692
OWL CM113	08:47:04	0.43	12.19	2.9	2.8	28	0.00667	0.00644	0.0644	8.13073	7.85036	78.5036	0.28681	0.27692
OWL CM113	08:46:58	0.43	12.19	3.2	2.8	28	0.00736	0.00644	0.0644	8.97184	7.85036	78.5036	0.31648	0.27692
OWL CM113	08:46:52	0.43	12.19	3.2	2.8	28	0.00736	0.00644	0.0644	8.97184	7.85036	78.5036	0.31648	0.27692
OWL CM113	08:46:46	0.43	12.19	3.2	2.8	28	0.00736	0.00644	0.0644	8.97184	7.85036	78.5036	0.31648	0.27692
OWL CM113	08:46:40	0.43	12.19	3.2	2.8	28	0.00736	0.00644	0.0644	8.97184	7.85036	78.5036	0.31648	0.27692
OWL CM113	08:46:34	0.43	12.19	3.2	2.8	28	0.00736	0.00644	0.0644	8.97184	7.85036	78.5036	0.31648	0.27692
OWL CM113	08:46:28	0.43	12.19	2.9	2.8	28	0.00667	0.00644	0.0644	8.13073	7.85036	78.5036	0.28681	0.27692
OWL CM113	08:46:22	0.43	12.19	2.9	2.8	28	0.00667	0.00644	0.0644	8.13073	7.85036	78.5036	0.28681	0.27692
OWL CM113	08:46:16	0.43	12.19	2.9	2.8	28	0.00667	0.00644	0.0644	8.13073	7.85036	78.5036	0.28681	0.27692
OWL CM113	08:46:10	0.43	12.19	3.2	2.8	28	0.00736	0.00644	0.0644	8.97184	7.85036	78.5036	0.31648	0.27692

5.3 EXPORTING HISTORICAL CHART DATA

Using the export function when viewing collected data will download the data depending upon option selected:-

- Data from current chart being displayed.
    - Viewing one hours data when exported will give that hours data on a per minute basis
    - Viewing one days data when exported will give that days data on a per minute basis
    - Viewing one month’s data when exported will give that months data on a per minute basis
    - Viewing one year’s data when exported will give that years data on a per minute basis
    - Viewing all data when exported will give all data on a per minute basis

- Data collected between 2 dates for sensor in current chart.
    - When exporting between 2 dates when one hours chart is being viewed only that hours data for the between those dates are exported on a per minute basis
    - When exporting between 2 dates when viewing all other charts all data between those dates is exported on a per minute basis.

- All data collected for sensor.
    - Exports all data for that sensor on a per minute basis.

5.4 HOW DO I USE THE CONVERTED DATA?

Device	Time	GHG_Factor	Tariff_Cost	Amps_Conv_Data (A)	Amps_Conv_Data_Min (A)	Amps_Conv_Data_Max (A)	kW_Conv_Data (kW)	kW_Conv_Data_Min (kW)	kW_Conv_Data_Max (kW)	Cost_Conv_Data (p/c)	Cost_Conv_Data_Min (p/c)	Cost_Conv_Data_Max (p/c)	GHG_Conv_Data (kg)	GHG_Conv_Data_Min (kg)
OWL CM119	01/03/2010 00:00	0.43	8.73	0.0124	0.0117	0.0128	0.0028	0.0003	0.0003	0.0248	0.0234	0.0258	0.0012	0.0012
OWL CM119	01/03/2010 00:01	0.43	8.73	0.0117	0.0117	0.0117	0.0027	0.0003	0.0003	0.0234	0.0234	0.0234	0.0012	0.0012
OWL CM119	01/03/2010 00:02	0.43	8.73	0.0121	0.0117	0.0128	0.0028	0.0003	0.0003	0.0244	0.0234	0.0258	0.0012	0.0012
OWL CM119	01/03/2010 [illegible]	[illegible]	[illegible]	[illegible]	0.0117	0.0128	0.0029	0.0003	0.0003	0.0251	0.0234	0.0258	0.0012	0.0012
OWL CM119	01/03/2010 [illegible]	[illegible]	[illegible]	[illegible]	0.0117	0.0128	0.0028	0.0003	0.0003	0.0241	0.0234	0.0258	0.0012	0.0012
OWL CM119	01/03/2010 [illegible]	[illegible]	[illegible]	[illegible]	0.0128	0.0128	0.0030	0.0003	0.0003	0.0258	0.0258	0.0258	0.0013	0.0013
OWL CM119	01/03/2010 [illegible]	[illegible]	[illegible]	[illegible]	0.0128	0.0128	0.0030	0.0003	0.0003	0.0258	0.0258	0.0258	0.0013	0.0013
OWL CM119	01/03/2010 00:07	0.43	8.73	0.0182	0.0128	0.0210	0.0042	0.0003	0.0005	0.0365	0.0258	0.0422	0.0018	0.0013
OWL CM119	01/03/2010 00:08	0.43	8.73	0.0222	0.0210	0.0233	0.0051	0.0005	0.0005	0.0445	0.0422	0.0469	0.0022	0.0021
OWL CM119	01/03/2010 00:09	0.43	8.73	0.0233	0.0233	0.0233	0.0054	0.0005	0.0005	0.0469	0.0469	0.0469	0.0023	0.0023
OWL CM119	01/03/2010 00:10	0.43	8.73	0.0233	0.0233	0.0233	0.0054	0.0005	0.0005	0.0469	0.0469	0.0469	0.0023	0.0023
OWL CM119	01/03/2010 00:11	0.43	8.73	0.0229	0.0222	0.0233	0.0053	0.0005	0.0005	0.0459	[illegible]	[illegible]	[illegible]	[illegible]
OWL CM119	01/03/2010 00:12	0.43	8.73	0.0222	0.0222	0.0222	0.0051	0.0005	0.0005	0.0445	[illegible]	[illegible]	[illegible]	[illegible]
OWL CM119	01/03/2010 00:13	0.43	8.73	0.0217	0.0210	0.0222	0.0050	0.0005	0.0005	0.0436	[illegible]	[illegible]	[illegible]	[illegible]
OWL CM119	01/03/2010 00:14	0.43	8.73	0.0210	0.0210	0.0210	0.0048	0.0005	0.0005	0.0422	[illegible]	[illegible]	[illegible]	[illegible]
OWL CM119	01/03/2010 00:15	0.43	8.73	0.0210	0.0210	0.0210	0.0048	0.0005	0.0005	0.0422	[illegible]	[illegible]	[illegible]	[illegible]
OWL CM119	01/03/2010 00:16	0.43	8.73	0.0210	0.0210	0.0210	0.0048	0.0005	0.0005	0.0422	[illegible]	[illegible]	[illegible]	[illegible]
OWL CM119	01/03/2010 00:17	[illegible]	[illegible]	[illegible]	[illegible]	0.0210	0.0048	0.0005	0.0005	0.0422	[illegible]	[illegible]	[illegible]	[illegible]
OWL CM119	01/03/2010 00:18	[illegible]	[illegible]	[illegible]	[illegible]	0.0210	0.0048	0.0005	0.0005	0.0422	0.0422	0.0422	0.0021	0.0021
OWL CM119	01/03/2010 00:19	[illegible]	[illegible]	[illegible]	[illegible]	0.0210	0.0048	0.0005	0.0005	0.0422	0.0422	0.0422	0.0021	0.0021
OWL CM119	01/03/2010 00:20	[illegible]	[illegible]	[illegible]	[illegible]	0.0210	0.0048	0.0005	0.0005	0.0422	0.0422	0.0422	0.0021	0.0021
OWL CM119	01/03/2010 00:21	[illegible]	[illegible]	[illegible]	[illegible]	0.0210	0.0048	0.0005	0.0005	0.0422	0.0422	0.0422	0.0021	0.0021
OWL CM119	01/03/2010 00:22	[illegible]	[illegible]	[illegible]	[illegible]	0.0210	0.0048	0.0005	0.0005	0.0422	0.0422	0.0422	0.0021	0.0021
OWL CM119	01/03/2010 00:23	[illegible]	[illegible]	[illegible]	[illegible]	0.0210	0.0047	0.0005	0.0005	0.0415	0.0398	0.0422	0.0020	0.0020
OWL CM119	01/03/2010 00:24	[illegible]	[illegible]	[illegible]	[illegible]	0.0210	0.0047	0.0005	0.0005	0.0408	0.0398	0.0422	0.0020	0.0020
OWL CM119	01/03/2010 00:25	[illegible]	[illegible]	[illegible]	[illegible]	0.0210	0.0048	0.0005	0.0005	0.0422	0.0422	0.0422	0.0021	0.0021
OWL CM119	01/03/2010 00:26	[illegible]	[illegible]	[illegible]	[illegible]	0.0210	0.0048	0.0005	0.0005	0.0422	0.0422	0.0422	0.0021	0.0021
OWL CM119	01/03/2010 00:27	0.43	8.73	0.0210	0.0210	0.0210	0.0048	0.0005	0.0005	0.0422	0.0422	0.0422	0.0021	0.0021
OWL CM119	01/03/2010 00:28	0.43	8.73	0.0184	0.0128	0.0210	0.0042	0.0003	0.0005	0.0370	0.0258	0.0422	0.0018	0.0013
OWL CM119	01/03/2010 00:29	0.43	8.73	0.0128	0.0128	0.0128	0.0030	0.0003	0.0003	0.0258	0.0258	0.0258	0.0013	0.0013
OWL CM119	01/03/2010 00:30	0.43	8.73	0.0128	0.0128	0.0128	0.0030	0.0003	0.0003	0.0258	0.0258	0.0258	0.0013	0.0013
OWL CM119	01/03/2010 00:31	0.43	8.73	0.0124	0.0117	0.0128	0.0028	0.0003	0.0003	0.0248	0.0234	0.0258	0.0012	0.0012
OWL CM119	01/03/2010 00:32	0.43	8.73	0.0117	0.0117	0.0117	0.0027	0.0003	0.0003	0.0234	0.0234	0.0234	0.0012	0.0012
OWL CM119	01/03/2010 00:33	0.43	8.73	0.0121	0.0117	0.0128	0.0028	0.0003	0.0003	0.0244	0.0234	0.0258	0.0012	0.0012
OWL CM119	01/03/2010 00:34	0.43	8.73	0.0124	0.0117	0.0128	0.0028	0.0003	0.0003	0.0248	0.0234	0.0258	0.0012	0.0012
OWL CM119	01/03/2010 00:35	0.43	8.73	0.0135	0.0128	0.0140	0.0031	0.0003	0.0003	0.0272	0.0258	0.0281	0.0013	0.0013
OWL CM119	01/03/2010 00:36	0.43	8.73	0.0131	0.0128	0.0152	0.0030	0.0003	0.0003	0.0262	0.0258	0.0305	0.0013	0.0013
OWL CM119	01/03/2010 00:37	0.43	8.73	0.0128	0.0128	0.0128	0.0030	0.0003	0.0003	0.0258	0.0258	0.0258	0.0013	0.0013
OWL CM119	01/03/2010 00:38	0.43	8.73	0.0131	0.0128	0.0152	0.0030	0.0003	0.0003	0.0262	0.0258	0.0305	0.0013	0.0013
OWL CM119	01/03/2010 00:39	0.43	8.73	0.0128	0.0128	0.0128	0.0030	0.0003	0.0003	0.0258	0.0258	0.0258	0.0013	0.0013
OWL CM119	01/03/2010 00:40	0.43	8.73	0.0125	0.0117	0.0128	0.0029	0.0003	0.0003	0.0251	0.0234	0.0258	0.0012	0.0012
OWL CM119	01/03/2010 00:41	0.43	8.73	0.0121	0.0117	0.0128	0.0028	0.0003	0.0003	0.0244	0.0234	0.0258	0.0012	0.0012
OWL CM119	01/03/2010 00:42	0.43	8.73	0.0124	0.0117	0.0128	0.0028	0.0003	0.0003	0.0248	0.0234	0.0258	0.0012	0.0012
OWL CM119	01/03/2010 00:43	0.43	8.73	0.0117	0.0117	0.0117	0.0027	0.0003	0.0003	0.0234	0.0234	0.0234	0.0012	0.0012
OWL CM119	01/03/2010 00:44	0.43	8.73	0.0119	0.0117	0.0140	0.0027	0.0003	0.0003	0.0239	0.0234	0.0281	0.0012	0.0012
OWL CM119	01/03/2010 00:45	0.43	8.73	0.0121	0.0117	0.0128	0.0028	0.0003	0.0003	0.0244	0.0234	0.0258	0.0012	0.0012
OWL CM119	01/03/2010 00:46	0.43	8.73	0.0128	0.0128	0.0128	0.0030	0.0003	0.0003	0.0258	0.0258	0.0258	0.0013	0.0013
OWL CM119	01/03/2010 00:47	0.43	8.73	0.0128	0.0128	0.0128	0.0030	0.0003	0.0003	0.0258	0.0258	0.0258	0.0013	0.0013
OWL CM119	01/03/2010 00:48	0.43	8.73	0.0128	0.0128	0.0128	0.0030	0.0003	0.0003	0.0258	0.0258	0.0258	0.0013	0.0013
OWL CM119	01/03/2010 00:49	0.43	8.73	0.0128	0.0128	0.0128	0.0030	0.0003	0.0003	0.0258	0.0258	0.0258	0.0013	0.0013
OWL CM119	01/03/2010 00:50	0.43	8.73	0.0124	0.0117	0.0128	0.0028	0.0003	0.0003	0.0248	0.0234	0.0258	0.0012	0.0012
OWL CM119	01/03/2010 00:51	0.43	8.73	0.0117	0.0117	0.0117	0.0027	0.0003	0.0003	0.0234	0.0234	0.0234	0.0012	0.0012
OWL CM119	01/03/2010 00:52	0.43	8.73	0.0196	0.0140	0.0210	0.0045	0.0003	0.0005	0.0394	0.0281	0.0422	0.0019	0.0014
OWL CM119	01/03/2010 00:53	0.43	8.73	0.0224	0.0210	0.0233	0.0052	0.0005	0.0005	0.0450	0.0422	0.0469	0.0022	0.0021
OWL CM119	01/03/2010 00:54	0.43	8.73	0.0233	0.0233	0.0233	0.0054	0.0005	0.0005	0.0469	0.0469	0.0469	0.0023	0.0023
OWL CM119	01/03/2010 00:55	0.43	8.73	0.0233	0.0233	0.0233	0.0054	0.0005	0.0005	0.0469	0.0469	0.0469	0.0023	0.0023
OWL CM119	01/03/2010 00:56	0.43	8.73	0.0233	0.0233	0.0233	0.0054	0.0005	0.0005	0.0469	0.0469	0.0469	0.0023	0.0023
OWL CM119	01/03/2010 00:57	0.43	8.73	0.0233	0.0233	0.0233	0.0054	0.0005	0.0005	0.0469	0.0469	0.0469	0.0023	0.0023
OWL CM119	01/03/2010 00:58	0.43	8.73	0.0233	0.0233	0.0233	0.0054	0.0005	0.0005	0.0469	0.0469	0.0469	0.0023	0.0023
OWL CM119	01/03/2010 00:59	0.43	8.73	0.0233	0.0233	0.0233	0.0054	0.0005	0.0005	0.0469	0.0469	0.0469	0.0023	0.0023
OWL CM119	01/03/2010 01:00	0.43	8.73	0.0231	0.0222	0.0257	0.0053	0.0005	0.0006	0.0464	0.0445	0.0515	0.0023	0.0022
OWL CM119	01/03/2010 01:01	0.43	8.73	0.0222	0.0222	0.0222	0.0051	0.0005	0.0005	0.0445	0.0445	0.0445	0.0022	0.0022
OWL CM119	01/03/2010 01:02	0.43	8.73	0.0217	0.0210	0.0222	0.0050	0.0005	0.0005	0.0436	0.0422	0.0445	0.0021	0.0021
OWL CM119	01/03/2010 01:03	0.43	8.73	0.0210	0.0210	0.0210	0.0048	0.0005	0.0005	0.0422	0.0422	0.0422	0.0021	0.0021
OWL CM119	01/03/2010 01:04	0.43	8.73	0.0210	0.0210	0.0210	0.0048	0.0005	0.0005	0.0422	0.0422	0.0422	0.0021	0.0021
OWL CM119	01/03/2010 01:05	0.43	8.73	0.0210	0.0210	0.0210	0.0048	0.0005	0.0005	0.0422	0.0422	0.0422	0.0021	0.0021
OWL CM119	01/03/2010 01:06	0.43	8.73	0.0210	0.0210	0.0210	0.0048	0.0005	0.0005	0.0422	0.0422	0.0422	0.0021	0.0021
OWL CM119	01/03/2010 01:07	0.43	8.73	0.0210	0.0210	0.0210	0.0048	0.0005	0.0005	0.0422	0.0422	0.0422	0.0021	0.0021

Min/Max Data is the minimum and maximum usage during the datapoint

The kW data is broken down into kWh used in a 1 minute period, so to get the kWh's used in one hour the sum of 1hours data needs to be taken

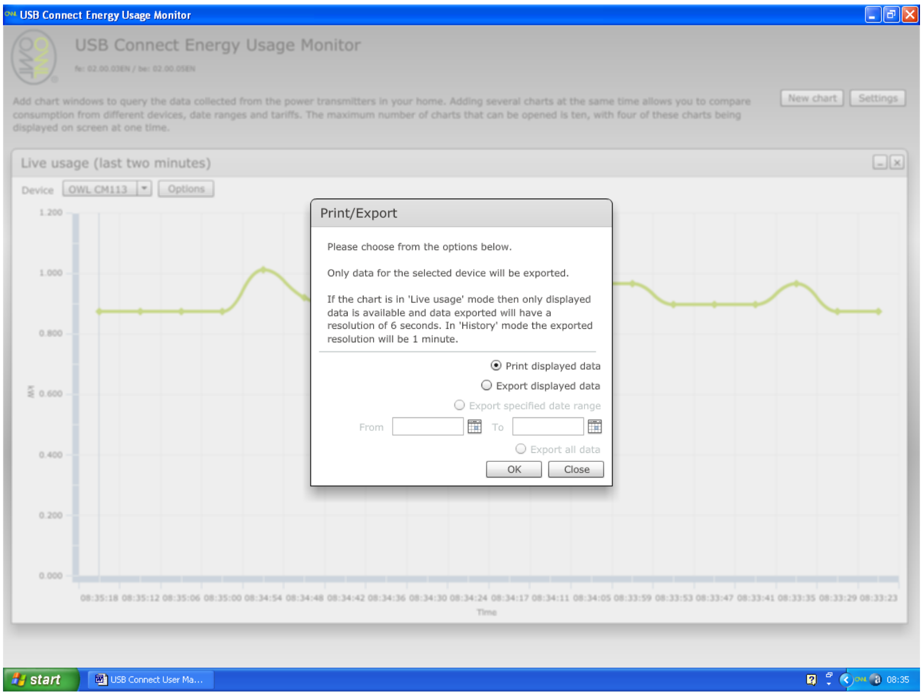
0.246kWh

To get the cost used in one hour the sum of 1hours data needs to be taken

2.147 pence / cents

7.0 CHART PRINTING

A simple version of the charts can be printed by selecting the Print option in the Export/Print menu.



Add chart windows to query the data collected from the power transmitters in your home. Adding several charts at the same time allows you to compare consumption from different devices, date ranges and tariffs. The maximum number of charts that can be opened is ten, with four of these charts being displayed on screen at one time.

Print/Export

Please choose from the options below.

Only data for the selected device will be exported.

If the chart is in 'Live usage' mode then only displayed data is available and data exported will have a resolution of 6 seconds. In 'History' mode the exported resolution will be 1 minute.

● Print displayed data

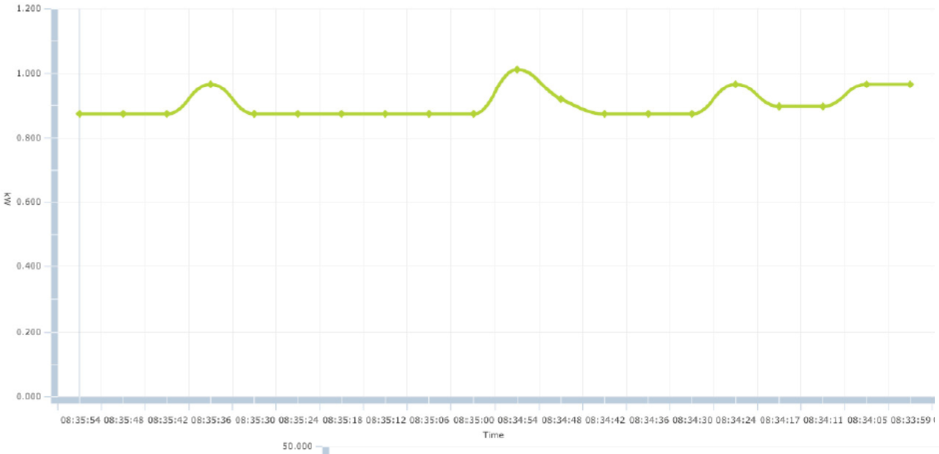
○ Export displayed data

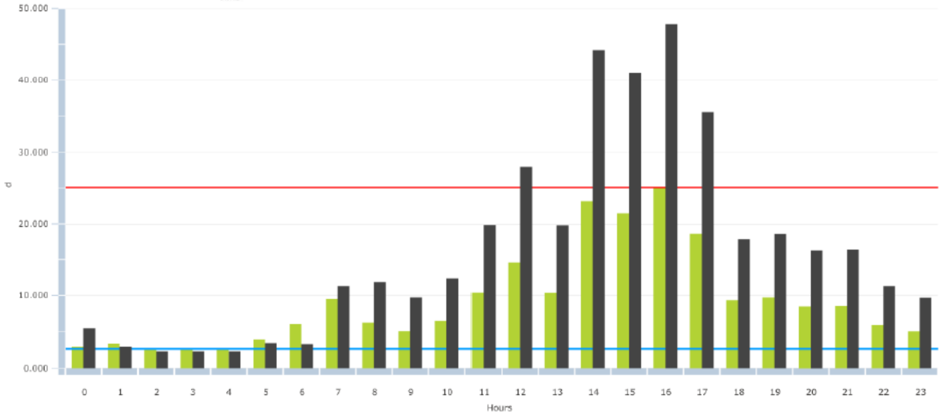
○ Export specified date range

From ☐ To ☐

○ Export all data

OK Close





OWL® intuition

Residential Heating & Hot Water Control

User Manual

For OWL Intuition Heating & Hot Water Controls

(All versions)

Room Sensor with Network OWL

Table of Contents

1. Introduction

OWL Intuition Residential Heating & Hot Water Controls are part of the OWL Intuition range of cloud connected monitoring and control products. This manual covers the operation of OWL Intuition for Central Heating systems - Combi, Regular, System, and Conventional, with or without a separate Hot Water tank / cylinder.

Operation of the various Room Sensors (room thermostat replacement) and Tank Sensors (hot water tank thermostat replacement) is dependant upon them being correctly paired to the Intuition Network OWL (supplied separately); this is plugged into your home broadband Internet router.

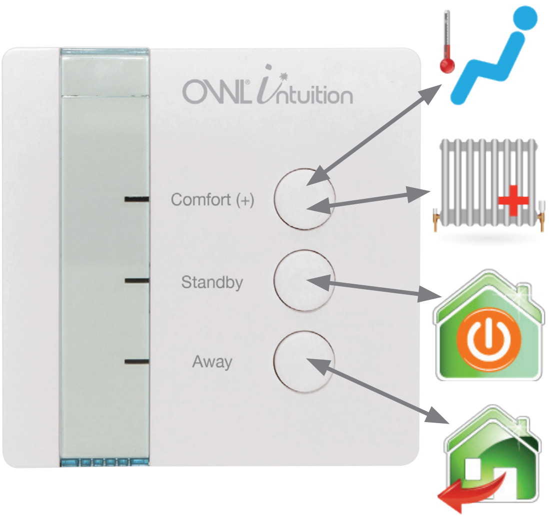
The Room Sensor and Tank Sensor each provide both thermostat and programmer / time clock functionality. Basic day-to-day user operation changes can be made using the three buttons.

OWL Intuition also provides remote control from any Internet connected computer anywhere in the World. You can securely log into the intuitive web dashboard through any modern web browser. iPhone and Android smartphone apps are also available for free download from the App Stores.

A wireless version of the Room Sensor and/or Tank Sensor is provided for by the addition of a OWL Intuition Relay Unit. Functional operation is the same for both wired and wireless versions. You can also use the buttons on the Relay Unit to control your heating.

For homes with more than one heating zone or more than one hot water tank you simply pair additional Room Sensors and/or Tank Sensors to the system. OWL Intuition will support up to 4 of each and meets with the requirements of Building Regulations Part L.

2. Quick Start - Heating Control Essentials



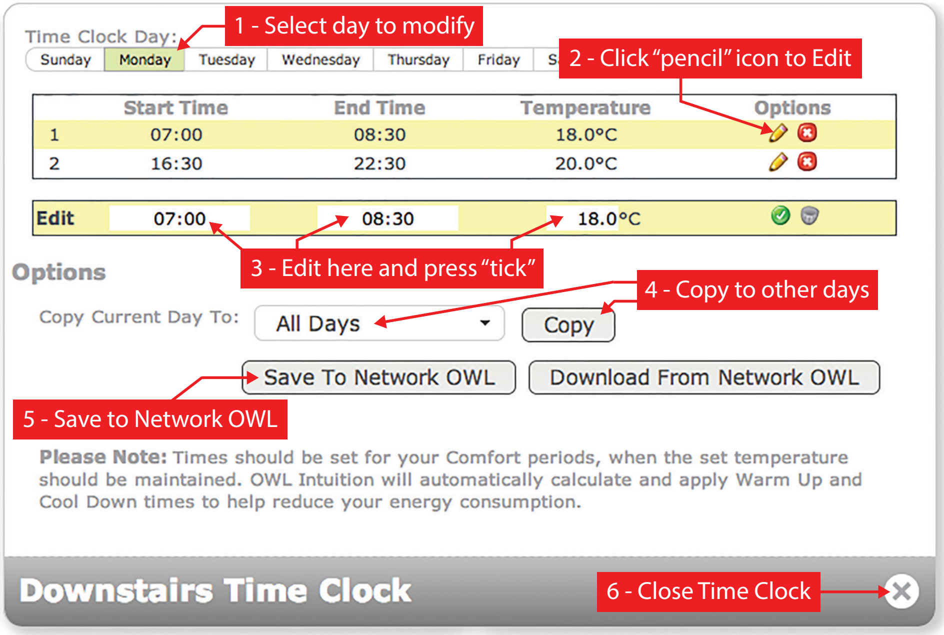
Comfort - your heating will be automatically managed to the temperatures set in the Time Clock. Press to start next defined period now.

Boost - press Comfort (+) button until LED starts flashing to boost current temperature. Cancels after set time period.

Standby - heating off until next Time Clock period. Press this if you want to cancel the current Comfort period.

Away - heating and hot water off until further notice (all zones). Press button until LED starts flashing to activate this mode.
Press Comfort or Standby to cancel.

Time Clock - ensure you have set up your Heating Time Clock for each heating zone within your system, e.g. Downstairs and Upstairs zones. Access in the Web Dashboard by clicking on the appropriate "Clock" icon. Set the times and temperatures to suit your home and lifestyle. These define the "Comfort" periods.



1 - Select day to modify

2 - Click "pencil" icon to Edit

3 - Edit here and press "tick"

4 - Copy to other days

5 - Save to Network OWL

6 - Close Time Clock

Time Clock Day:

Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | S

	Start Time	End Time	Temperature	Options
1	07:00	08:30	18.0°C	✎ ☒
2	16:30	22:30	20.0°C	✎ ☒
Edit	07:00	08:30	18.0°C	✓

Options

Copy Current Day To: All Days ▾ Copy

Save To Network OWL | Download From Network OWL

Please Note: Times should be set for your Comfort periods, when the set temperature should be maintained. OWL Intuition will automatically calculate and apply Warm Up and Cool Down times to help reduce your energy consumption.

Downstairs Time Clock

3. Quick Start - Hot Water Control Essentials

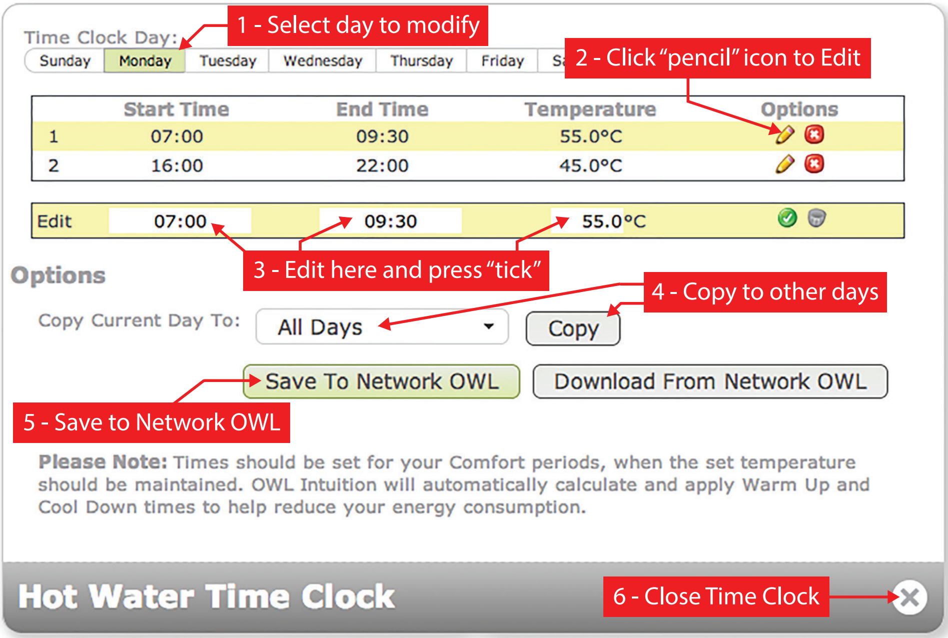
Comfort - press to start Comfort mode for ALL heating zones now.

Boost - press Comfort (+) button until LED starts flashing to boost ALL heating zones. Cancels after set time period.

Standby - ALL heating zones off until next Time Clock period.

More Hot Water - press to immediately heat the hot water to set temperature (one shot).

Time Clock - ensure you have set up your Heating Time Clock for each hot water zone within your system, e.g. Tank One and Tank Two. Access in the Web Dashboard by clicking on the appropriate "Clock" icon. Set the times and temperatures to suit your home and lifestyle. Times set define when the hot water temperature will be managed.



Time Clock Day: Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | Sa

1 - Select day to modify

2 - Click "pencil" icon to Edit

	Start Time	End Time	Temperature	Options
1	07:00	09:30	55.0°C	✎ ✖
2	16:00	22:00	45.0°C	✎ ✖

Edit 07:00 09:30 55.0°C ✓

3 - Edit here and press "tick"

Options

Copy Current Day To: All Days ▾ Copy

4 - Copy to other days

Save To Network OWL   Download From Network OWL

5 - Save to Network OWL

Please Note: Times should be set for your Comfort periods, when the set temperature should be maintained. OWL Intuition will automatically calculate and apply Warm Up and Cool Down times to help reduce your energy consumption.

Hot Water Time Clock

6 - Close Time Clock

4. Before You Continue

This manual assumes that your Network OWL Gateway has been successfully installed and your OWL Intuition account has been registered. Please refer to the manual supplied with the Network OWL for further instructions if required. You will need your Username and Password to be able to log into the OWL Intuition web dashboard. If you also have an OWL Intuition Electricity monitoring Transmitter to install then you should pair this device before proceeding. Please refer to the Instructions provided with that product for details.

a. Heating (OWL Intuition-c & -cw)

For a newly installed OWL Intuition-c or -cw system it is essential that the following steps are all completed.

i. Install Network OWL and create OWL Intuition account. (Separate document)
ii. Install Room Sensor (& Relay Unit for wireless systems). (Separate documents)
iii. Set up Heating Time Clock to suit your requirements. (Section 4b)
iv. Adjust any Heating default settings to suit your requirements. (Section 4e)
v. Repeat from step ii. for any additional heating zone Room Sensors.

b. Hot Water (OWL Intuition-h & -hw)

For a newly installed OWL Intuition-h or -hw system it is essential that the following steps are all completed.

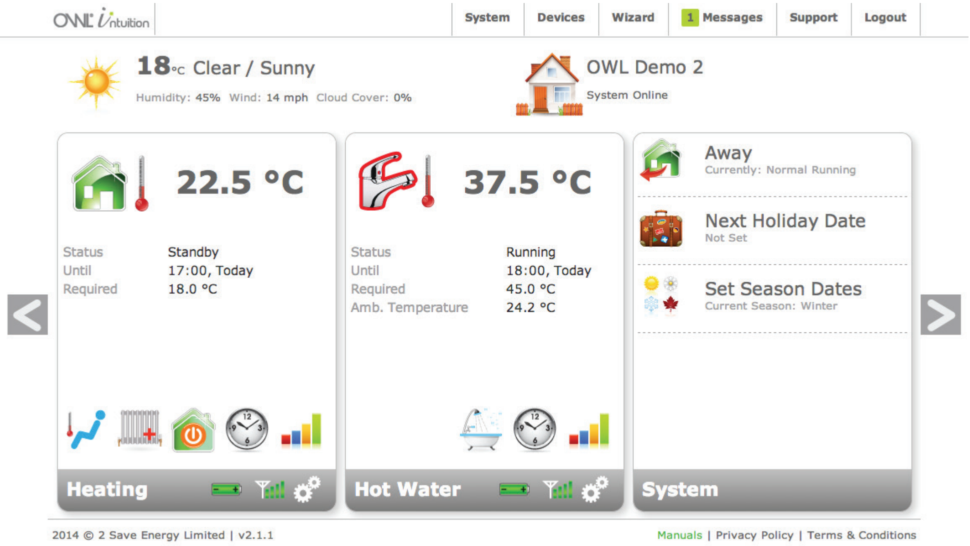
i. All steps shown for Heating above.
ii. Install Tank Sensor (& Relay Unit for wireless systems). (Separate documents)
iii. Set up Hot Water Time Clock to suit your requirements. (Section 4b)
iv. Adjust any Hot Water default settings to suit your requirements. (Section 4e)
v. Repeat from step ii. for any additional hot water Tank Sensors.

5. Operational Overview

a. General

Once installed and configured your OWL Intuition system should give you many years of intelligent, energy-saving, remotely operable Central Heating control.

OWL Intuition can be configured and controlled using an intuitive web dashboard across the Internet through a standard web browser on any Internet connected computer, tablet or smartphone. This allows you to operate from your office computer whilst you are at work or maybe using your iPhone whilst enjoying an evening out with friends.



18°C Clear / Sunny

Humidity: 45% Wind: 14 mph Cloud Cover: 0%

OWL Demo 2

System Online

22.5 °C

Status Standby
Until 17:00, Today
Required 18.0 °C

37.5 °C

Status Running
Until 18:00, Today
Required 45.0 °C
Amb. Temperature 24.2 °C

Away
Currently: Normal Running

Next Holiday Date
Not Set

Set Season Dates
Current Season: Winter

2014 © 2 Save Energy Limited | v2.1.1

OWL Intuition Web Dashboard - (with Heating and Hot Water)

OWL Intuition automatically obtains the current date and time from OWL's servers and will automatically adjust itself for British Summer Time and Greenwich Mean Time changes (daylight saving time). It stores a time clock for up to 10 x Comfort (heating) periods for each heating zone Room Sensor and 5 x Hot Water periods per day for each hot water Tank Sensor. The system will continue to run, even during periods of Internet down time.

You can set Season dates to ensure your heating is turned off during the Summer. Set Holiday dates and times so that you don't waste energy whilst you are away from home, but ensure it will be nice and warm for your return.

The Network OWL, Room Sensor, Tank Sensor & Relay Unit internal firmware (software) can be upgraded over the Internet / radio link from OWL's servers - so future improvements, new features or any software updates can be easily applied as required.

OWL Intuition brings your home into the Internet Age!

b. Heating (OWL Intuition-c)

Room Sensor

The Room Sensor replaces your existing room thermostat and is typically installed in your lounge or hall. It is wirelessly paired with the Network OWL Gateway device. The Room Sensor provides simple day to day control for the heating. You can activate heating Boost, switch between Comfort, Standby or Away modes by pressing the Room Sensor buttons.

i. ***Room Sensor [RBT-3C]***

Battery powered so it does not need mains power wiring to be installed. This version requires wiring back to the boiler / wiring centre.

The Room Sensor has a simple 3 button user interface, with Comfort (+), Standby and Away buttons.

Fitted with a highly accurate digital temperature sensor, a low power latching relay (wired heating on/off control) and a radio connected micro computer running OWL's latest advanced over air upgradable heating control software.

ii. ***Room Sensor [RBH-3C]***

Identical to Room Sensor [RBT-3C] but also has accurate digital humidity sensor.

c. Hot Water (OWL Intuition-h)

Tank Sensor

The Tank Sensor is wired in series with your existing hot water tank thermostat. The Tank Sensor itself is typically installed adjacent to your hot water tank / cylinder, maybe on your landing if the tank is in your airing cupboard. It is wirelessly paired with the Network OWL Gateway device.

The Tank Sensor provides simple day to day control for your hot water and also your heating. You can activate the More Hot Water function by pressing the More H/W button. Additionally you can activate heating Boost or switch between heating Comfort and Standby.

i. ***Tank Sensor [TBTE3H]***

Battery powered so it does not need mains power wiring to be installed. This version requires wiring back to the boiler / wiring centre. The Tank Sensor has a cable connected (3m) accurate digital Temperature Sensor which is fitted to the side of the hot water tank / cylinder.

The Tank Sensor has a simple 3 button user interface, with Comfort (+), Standby and

More H/W buttons.

Also fitted with a highly accurate digital temperature sensor, a low power latching relay (wired hot water on/off control) and a radio connected micro computer running OWL's latest advanced over air upgradable hot water control software.

ii. Tank Sensor [TBHE3H]

Identical to Tank Sensor [TBTE3H] but also has accurate digital humidity sensor.

d. Wireless Relay Unit (OWL Intuition-cw & -hw)

If you don't have wiring available from your chosen Room Sensor and/or Tank Sensor location back to the boiler / wiring centre then the OWL Intuition Relay Unit can be used to provide wireless connectivity.

The Relay Unit is therefore typically installed physically next to your boiler / wiring centre. It is also wirelessly paired with the Network OWL Gateway device. However, additionally it is also wirelessly paired to the Room Sensors and/or Tank Sensors that need to be able to "call for heat". If you have any Relay Units installed, you can also use them to activate heating Boost, switch between Comfort, Standby or Away modes by pressing the Relay Unit buttons.

Relay Unit

6. Heating Control

a. Heating Modes of Operation

Your OWL Intuition heating control manages the temperature of your home at all times (24 hours per day, 7 days per week, 365 days of the year). Each heating zone Room Sensor is always in one of the following five modes:

i. Comfort Period

Like a conventional heating control, the Heating Time Clock initially defines at what times you would like your home to be maintained at a comfortable Target temperature. These periods are known as Comfort Periods.

a. Warm Up - Unlike most heating controls, OWL Intuition is intelligent and calculates at what time it needs to switch the heating on to be at your Target temperature for the Start Time you have defined. OWL Intuition takes into account different factors such as your current local weather conditions.

b. Cool Down - Likewise OWL Intuition will determine when to switch the heating off, in advance of the Comfort heating period ending.

Intelligent Warm Up and Cool Down take the guesswork out of making your home comfortable for the times you need, whilst saving energy.

c. Boost - If you are feeling cold then the Heating Boost function will turn the heating on (if necessary) with a target of current room temperature + 1°C for one hour and then revert to previous mode and settings. You can configure temperature and time to suit your personal preferences (Heating Settings).

ii. Standby Period

In normal day-to-day operation, whenever OWL Intuition is not in a Comfort Period, it is in Standby mode. During these periods OWL Intuition will maintain a single Target temperature (configurable). For best economy your Standby temperature would normally be set at a low enough level such that the Standby heating will only come on during exceptionally cold weather.

iii. Away

When you are away from your home for an extended period of time, OWL Intuition can be put into a special Away mode. When in Away mode, OWL Intuition will maintain a frost protection temperature (configurable) for your home and hot water tank (if Tank Sensor is also installed).

iv. Holiday

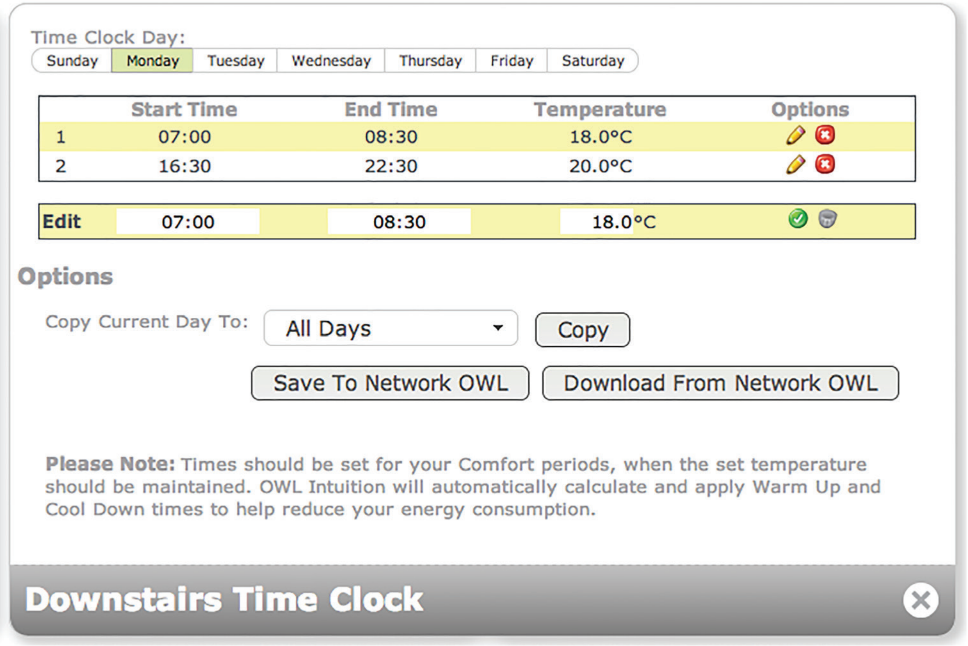
Similar to Away mode, OWL Intuition can be preset as to when you will be away on holiday (start date & return date). When in Holiday mode, OWL Intuition will maintain a single Target temperature (configurable) for your home and hot water tank (if Tank Sensor is also installed).

v. Summer Mode

OWL Intuition automatically switches to Summer Mode between user configurable start and end dates. When in Summer Mode, OWL Intuition will maintain a frost protection temperature (configurable) for your home. When in Summer Mode, you can revert to the normal heating time clock by pressing the Comfort button. At midnight Summer Mode will be automatically activated again. Hot Water control, if fitted, is NOT affected by Summer Mode.

b. Heating Time Clock Setting

The Heating Time Clock defines the periods during which your home is automatically heated and to what temperature. These periods are called Comfort Periods (see Heating Modes of Operation above). OWL Intuition will intelligently calculate what time to switch the boiler on and off to maintain the target temperature for the whole of the Comfort Period. Each day of the week can be programmed with up to 10 different Comfort Periods.



	Start Time	End Time	Temperature	Options
1	07:00	08:30	18.0°C	✎ ✖
2	16:30	22:30	20.0°C	✎ ✖

Edit	07:00	08:30	18.0°C	✓ 🗑

Options

Copy Current Day To: All Days

Please Note: Times should be set for your Comfort periods, when the set temperature should be maintained. OWL Intuition will automatically calculate and apply Warm Up and Cool Down times to help reduce your energy consumption.

Downstairs Time Clock

OWL Intuition Web Dashboard - Heating Time Clock

The default Time Clock settings are shown in the table opposite. These can be modified using the OWL Intuition web dashboard.

- On the Heating widget click on the “Clock” icon. This opens the Heating Time Clock widget.
- Select the day you wish to amend, then click an option on the line you wish to amend.
  - Pencil icon to edit the line.
  - Cross icon to delete the line.
- Amend details within the Edit box as required then click on the Tick icon to update the table.
- To add a new line simply fill in the Add box with the required details and click on the Tick icon.
- When you are happy with your changes you can use the Copy Current Day feature to quickly duplicate to other days.
- **IMPORTANT:** When you have finished making changes you must save them to your

Network OWL by clicking on the “Save To Network OWL” button.

Preset Heating ‘Comfort’ Time Clock Settings

Monday to Friday		
Start Time	**End Time**	**Temperature**
07:00	08:30	18°C
16:30	22:30	20°C
Saturday & Sunday		
Start Time	**End Time**	**Temperature**
07:30	10:00	18°C
16:30	22:30	20°C

Note: Outside of these preset heating ‘Comfort’ periods, the Room Sensor will be in Standby mode (15°C - configurable).

c. Room Sensor Buttons & LED Functionality

The Room Sensor has three buttons, each with an associated indicator LED. They provide quick access to the most important heating control functions without needing to use your computer or smartphone.

Each button can have one or two related functions. Selection of the function is based upon how long the button is pressed.

i. Short Press

Make a single deliberate button press (up to 2 seconds).

ii. Long Press

Make a single deliberate button press and hold the button down until the associated LED indicator starts flashing, then release (3 to 8 seconds).

Room Sensor [RBx-3C]

Comfort (+) LED Meanings

▶ Single flash every 10 seconds
Heating ON but less than Target temp

▶ ▶ Double flash every 10 seconds
Heating ON and up to Target temp

▶ ▶ ▶ Triple flash every 10 seconds
Boost mode - Heating ON

Standby - LED Meaning

▶ Single flash every 10 seconds
Heating OFF until next Comfort period

Away - LED Meanings

▶ Single flash every 30 seconds
Away mode - Heating & Hot Water OFF

▶ ▶ Double flash every 30 seconds
Summer mode - Heating OFF, Hot Water ON

▶ ▶ ▶ Triple flash every 30 seconds
Holiday mode - Heating & Hot Water OFF

Comfort (Boost) - Heating ON

☛(1s) Short Press - Start next Comfort period now
☛(5s) Long Press - Boost mode / cancel
☛(1s) To Cancel Away mode and start Comfort period
☛(1s) To Cancel Summer mode and return to normal time clock until midnight

Standby - Heating OFF (temporary)

☛(1s) Short Press - Standby until next Comfort period
☛(5s) Long Press - Standby until midnight
☛(1s) To Cancel Away mode - Standby until next Comfort period

Away - Heating & Hot Water OFF

☛(1s) Short Press - No action
☛(5s) Long Press - Away temp until you Cancel
☛(1s) To Cancel Away mode and return to normal time clock

Button Press LED Meanings

◉ Solid for 5 seconds - Confirmation of button press

▶ ▶ ▶ Rapid flashing - Long press confirmation, release button now

d. Heating Web Dashboard Controls

Comfort

If you are feeling cold and would like the heating to come on then you should click on the Comfort icon. The heating will then remain in Comfort mode until the end of the next Time Clock scheduled period.

Heating Boost

Clicking on the Heating Boost icon will turn the heating on (if necessary) with a target of current room temperature + 1°C for one hour and then revert to previous mode and settings. You can configure temperature and time to suit your personal preferences (Heating Settings).

Standby

If you are feeling too warm, or leaving your home unoccupied and would like the heating to turn off then you should click on the Standby button. The heating will remain in Standby mode until the start of the next Time Clock scheduled period.

Time Clock

Opens the Heating Time Clock widget where you set the Comfort Periods that you desire for each day of the week. OWL Intuition will intelligently calculate what time to switch the boiler on and off to maintain the target temperature for the whole of the Comfort Period.

Heating Graphs

Displays temperatures for the past 7 days. *Temperature* shows the Room Sensor temperature. *Required Temperature* shows the actual heating Target temperatures (includes Time Clock, Warm Up, Cool Down and manual interventions). *External Temperature* is from Internet sourced weather.

e. Heating Settings

You can make any necessary changes to the various Heating settings by clicking on the “gear wheels” icon on the grey Heating widget title bar.

The various settings are detailed below, the default values are highlighted in **Bold**. Be sure to click the “Save” button before closing the window.

Target Temperatures

Mode	Default	Minimum	Maximum	Units
Comfort Period	As set in Heating Time Clock	5	35	°C
Standby	**15**	5	25	°C
Away	**5**	2	15	°C
Holiday	**5**	2	15	°C

Heating Features

<table>
<tr><th>Feature</th><th>Description</th></tr>
<tr><td>Boost Temperature Increment</td><td>This is the temperature that the current Target temperature will be increased by when the “Boost” feature is activated.
<table>
<tr><td>Default</td><td>Minimum</td><td>Maximum</td><td>Units</td></tr>
<tr><td>1.0</td><td>0.5</td><td>5.0</td><td>°C</td></tr>
</table></td></tr>
<tr><td>Boost Temperature Period</td><td>This is the time period that the “Boost” temperature will be applied for.
<table>
<tr><td>Default</td><td>Minimum</td><td>Maximum</td><td>Units</td></tr>
<tr><td>60</td><td>15</td><td>120</td><td>Minutes</td></tr>
</table></td></tr>
</table>

7. Hot Water Control

a. Hot Water Modes of Operation

Your OWL Intuition hot water control manages the temperature of your hot water at all times (24 hours per day, 7 days per week, 365 days of the year). Each hot water Tank Sensor is always in one of the following modes:

i. Running

Like a conventional control, the Hot Water Time Clock initially defines at what times you would like your hot water to be maintained at your chosen Target temperature. These periods are known as Hot Water Running Periods.

a. Warm Up - Unlike most controls, OWL Intuition is intelligent and calculates at what time it needs to switch the heating on for your hot water to be at your Target temperature for the Start Time you have defined. OWL Intuition takes into account different factors such as your the current hot water temperature.

b. Cool Down - Likewise OWL Intuition will determine when to switch the heating off, in advance of the Hot Water heating period ending.

Intelligent Warm Up and Cool Down take the guesswork out of ensuring your hot water is ready for the times you need, whilst saving energy.

ii. Off (Standby)

In normal day-to-day operation, whenever OWL Intuition is not in a Hot Water Running Period, it is Off (Standby). During these periods OWL Intuition will maintain a single Target Standby temperature (configurable). For best economy your Standby temperature would normally be set at a low enough level such that the Standby hot water heating will only come on during exceptionally cold weather.

iii. Away

When you are away from your home for an extended period of time, OWL Intuition can be put into a special Away mode. When in Away mode, OWL Intuition will maintain a frost protection temperature (configurable) for your hot water tank and home heating.

iv. Holiday

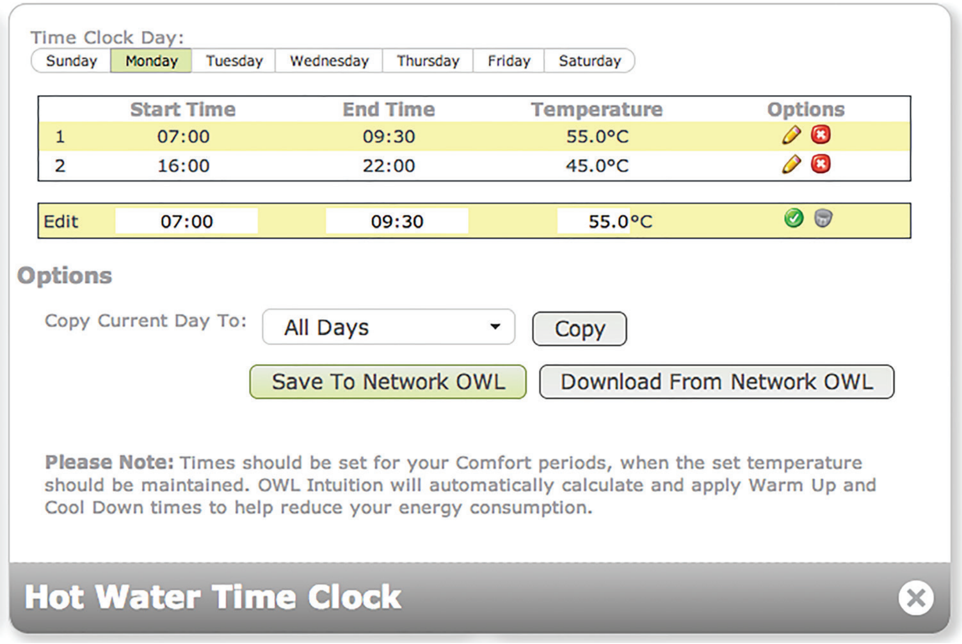
Similar to Away mode, OWL Intuition can be preset as to when you will be away on holiday (start date & return date). When in Holiday mode, OWL Intuition will maintain a single Target temperature (configurable) for your home and hot water tank (if Tank Sensor is also installed).

v. More Hot Water

If at you decide to have a bath or a shower at a time when the temperature of your hot water tank is too low, then you can boost the hot water temperature to 55°C for 30 minutes and then revert to previous mode and settings. You can configure temperature and time period to suit your personal preferences (Hot Water Settings).

b. Hot Water Time Clock Setting

The Hot Water Time Clock defines the periods during which your hot water is automatically heated and to what temperature. These periods are called Hot Water Running Periods (see Hot Water Modes of Operation above). OWL Intuition will intelligently calculate what time to switch the boiler on and off to maintain the target temperature hot water for the whole of the period. Each day of the week can be programmed with up to 5 different Hot Water Running Periods.



	Start Time	End Time	Temperature	Options
1	07:00	09:30	55.0°C	✎ ⊗
2	16:00	22:00	45.0°C	✎ ⊗
Edit	07:00	09:30	55.0°C	✓

Options

Copy Current Day To: All Days

Please Note: Times should be set for your Comfort periods, when the set temperature should be maintained. OWL Intuition will automatically calculate and apply Warm Up and Cool Down times to help reduce your energy consumption.

OWL Intuition Web Dashboard - Hot Water Time Clock

The default Time Clock settings are shown in the table below. These can be modified using the OWL Intuition web dashboard.

- On the Hot Water widget click on the "Clock" icon. This opens the Hot Water Time Clock widget.
- Select the day you wish to amend, then click an option on the line you wish to amend.
    - Pencil icon to edit the line.
    - Cross icon to delete the line.
- Amend details within the Edit box as required then click on the Tick icon to update the table.
- To add a new line simply fill in the Add box with the required details and click on the Tick icon.
- When you are happy with your changes you can use the Copy Current Day feature to quickly duplicate to other days.

- **IMPORTANT:** When you have finished making changes you must save them to your Network OWL by clicking on the “Save To Network OWL” button.

Preset Hot Water ‘Running’ Time Clock Settings

Monday to Friday		
Start Time	**End Time**	**Temperature**
06:30	08:00	55°C
16:00	22:00	45°C
Saturday & Sunday		
Start Time	**End Time**	**Temperature**
07:00	09:30	55°C
16:00	22:00	45°C

Note: Outside of these preset hot water heating periods, the Tank Sensor will maintain the how water Standby temperature (10°C - configurable).

c. Tank Sensor Buttons & LED Functionality

The Tank Sensor has three buttons, each with an associated indicator LED. They provide quick access to the most important hot water and heating control functions without needing to use your computer or smartphone.

Each button can have one or two related functions. Selection of the function is based upon how long the button is pressed.

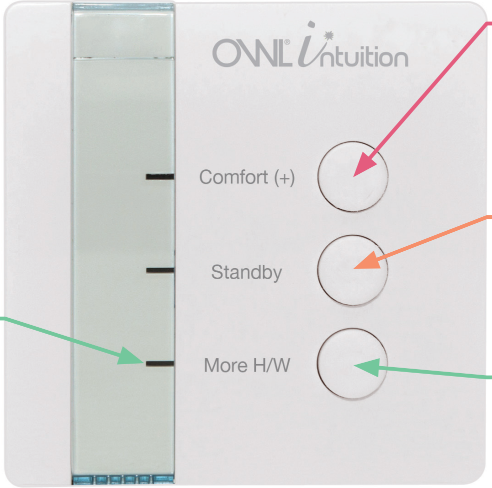
i. Short Press

Make a single deliberate button press (up to 2 seconds).

ii. Long Press

Make a single deliberate button press and hold the button down until the associated LED indicator starts flashing, then release (3 to 8 seconds).

Tank Sensor [TBxE3H]



Comfort (Boost) - Heating ON

☛(1s) Short Press - Start next Comfort period now
☛(5s) Long Press - Boost mode / cancel
☛(1s) To Cancel Away mode and start Comfort period
☛(1s) To Cancel Summer mode and return to normal time clock until midnight

Standby - Heating OFF (temporary)

☛(1s) Short Press - Standby until next Comfort period
☛(5s) Long Press - Standby until midnight
☛(1s) To Cancel Away mode - Standby until next Comfort period

More Hot Water - Boost Hot Water Temperature

☛(1s) Short Press - Boost Hot Water temperature
☛(5s) Long Press - Boost Hot Water to 65°C
☛(1s) To Cancel More Hot Water

More Hot Water - LED Meanings

▶ Single flash every 10 seconds Hot Water heating - time clock

▶ ▶ Double flash every 10 seconds Hot Water heating - More Hot Water

Button Press LED Meanings

◉ Solid for 5 seconds - Confirmation of button press

▶ ▶ ▶ Rapid flashing - Long press confirmation, release button now

d. Hot Water Web Dashboard Controls

More Hot Water

If at you decide to have a bath or a shower at a time when the temperature of your hot water tank is too low, then you can boost the hot water temperature to 55°C for 30 minutes and then revert to previous mode and settings. You can configure temperature and time period to suit your personal preferences (Hot Water Settings).

Time Clock

Opens the Hot Water Time Clock widget where you set the Hot Water Running Periods that you desire for each day of the week. OWL Intuition will intelligently calculate what time to switch the boiler on and off to maintain the target temperature for the whole of the period.

Hot Water Graphs

Displays hot water temperatures for the past 7 days. *Temperature* shows the hot water tank Temperature Sensor temperature. *Required Temperature* shows the actual hot water Target temperatures (includes Time Clock, Warm Up, Cool Down and manual More Hot Water interventions).

e. Hot Water Settings

You can make any necessary changes to the various Hot Water settings by clicking on the "gear wheels" icon on the grey Hot Water widget title bar.

The various settings are detailed below, the default values are highlighted in **Bold**. Be sure to click the "Save" button before closing the window.

Target Temperatures

Mode	Default	Minimum	Maximum	Units
Hot Water Running Period	As set in Hot Water Time Clock	5	65	°C
Standby	**10**	5	62	°C
Away	**10**	5	62	°C
Holiday	**10**	5	62	°C

Hot Water Features

<table>
<tr><th>Feature</th><th>Description</th></tr>
<tr><td>More Hot Water Temperature</td><td>This is the temperature to which the hot water will be heated when the "More Hot Water" feature is activated.
<table>
<tr><td>Default</td><td>Minimum</td><td>Maximum</td><td>Units</td></tr>
<tr><td>55</td><td>5</td><td>62</td><td>°C</td></tr>
</table></td></tr>
</table>

<table>
<tr><th>Feature</th><th>Description</th></tr>
<tr><td>More Hot Water-Period</td><td>This is the time period that the “More Hot Water” feature will run for.<table><tr><td>Default</td><td>Minimum</td><td>Maximum</td><td>Units</td></tr><tr><td>30</td><td>1</td><td>360</td><td>Minutes</td></tr></table></td></tr>
<tr><td>Hot Water Temperature Set Point Hysteresis</td><td>When the Tank Sensor’s digital Temperature Sensor reaches the defined Target temperature the boiler will be turned off. The system will then wait for the measured temperature to drop by 15% of the Target temperature before switching back on.</td></tr>
</table>

f. Hot Water Safety Measures

i. Temperature Sensor Disconnection

The Tank Sensor will detect and report via the web dashboard if the hot water tank / cylinder Temperature Sensor becomes disconnected. In these circumstances the hot water heating will cease until this condition is rectified. Please consult your heating maintenance engineer if required.

ii. Temperature Sensor Detachment

The Tank Sensor will detect a condition where the hot water heating is Running but where the Temperature Sensor is not reporting the associated and expected rise in hot water temperature. In these circumstances the hot water heating will cease until the end of the current Running period and a warning message will be sent via the web dashboard.

This potential fault condition will automatically clear itself at the end of the current Running period. If you see this potential fault reported then please ensure that the Temperature Sensor is correctly positioned / attached to the side of the hot water tank / cylinder. Please consult your heating maintenance engineer if required.

Please note that some System boilers with an integrated hot water tank / cylinder have their own temperature control built-in. This can have the effect of not allowing the boiler to run, even though the Intuition Tank Sensor is calling for heat, and thus creating this “potential fault condition” to occur. If this is the case with your system, then the Temperature Sensor Detachment safety feature can be disabled via Hot Water settings. Please consult your heating maintenance engineer for advice if required.

8. System Widget

a. System Widget Dashboard Controls

Away - (heating and hot water)

When you are away from your home for an extended period of time, OWL Intuition can be put into a special Away mode. When in Away mode, OWL Intuition will maintain a frost protection temperature whilst you are away. You can configure the temperature to suit your personal preferences (Heating & Hot Water Settings).

Next Holiday Date - (heating and hot water)

Let OWL Intuition know when you are going to be away on holiday and it will remember to manage your heating for you from when you leave until you return. The system will enter a special Away mode for the duration and maintain your chosen temperature. You can configure the temperature to suit your personal preferences (Heating & Hot Water Settings).

Set Season Dates - (heating only)

You should set the heating season start and end dates to suit your preferences. The Winter season is the period during which the heating Time Clock if enabled. If during the Summer season there is a cold day then simply click on the Comfort button and the heating Time Clock will be enabled for the rest of the day. Default season changeover dates are 23rd May and 23rd September.

9. Menu Bar Items

a. System Menu

i. *Account Settings*

Change Password - If you wish to change your account login password then select this option. Please ensure you remember your new password.

Email - This is your contact email address that will be used for future OWL Intuition system notifications and messages. Please ensure this is always a current and valid email address or you may miss important information about your system.

Timezone - Used to change the global timezone used for this system.

Currency - Used to change the currency used for this system.

ii. *Property Settings*

EPC Rating - It is important that you enter the actual Energy Performance Certificate ("EPC") rating for your home if you have one. If you don't have an EPC just estimate how you would rate the energy efficiency of your property on the A to G scale below.

Be sure to click the "Save" button before closing the window.

Property EPC / Energy Efficiency Rating

Rating	Score	Description
A	92+	Exceptional
B	81 - 91	Above Average
C	69 - 80	
D	**55 - 68**	**UK Average**
E	39 - 54	
F	21 - 38	Below Average
G	1 - 20	

Property Voltage - This is the mains voltage at the property. Using a measured value will provide better accuracy when using optional electricity / solar PV monitoring. If required you can also adjust the power factor used in these calculations.

Country - You should ensure that your country is correctly set here.

Postcode/Town - Only the first part of your UK postcode is required or your Town if you are outside of the United Kingdom. This information is used to source the weather information used and displayed by the system.

Property Label - It you change this then the web dashboard (and smartphone apps) will display this instead of the default "Network OWL" at the top of the screen.

iii. *Advanced Settings*

Setup Data Push - Allows you to push your Intuition data in near real-time to an external IP address / port. Data is sent, "fire and forget" using the UDP protocol in an XML data structure. Please click on "Support" on the menu bar if you require further information on this advanced feature.

b. Devices Menu

i. Device List

You can see details about your Network OWL and all of the Intuition devices that are currently paired to your Network OWL. Whilst viewing device details you upgrade the devices firmware (if a later version has been released) you can also delete devices and change the batteries on OWL Electricity Transmitters.

ii. Find Devices

If you click on the "Find" button you the OWL Intuition Configuration Wizard will start allowing you to add Electricity Transmitters and other Intuition Devices.

c. Wizard

Opens the OWL Intuition Configuration Wizard to allow you to extend your system with additional OWL Intuition products. Please follow the Installation Instructions supplied with the new hardware.

d. Messages

Here you will see a list of the messages that you have been sent. Whenever there is a new message a green "badge" will appear next to the menu bar text Messages. Please read these messages as soon as they appear. They may include important information including safety warnings. Messages can be deleted after reading if you desire.

e. Support

If you need further help or support with your OWL Intuition system then this will open a new browser tab with the OWL Zendesk support system. Here you can browse or search for articles answering most common queries and issues. If you are unable to find the answer you require, then you can click on "Submit a request". This will open a support ticket that will be answered by one of our Customer Services team.

f. Logout

When you have finished using the OWL Intuition web dashboard then for security please click here to logout.

10. Important Information

- OWL Intuition heating and hot water controls are designed to intelligently help you save energy and money. Actual savings depend upon individual home and heating system characteristics, lifestyle / occupancy patterns and set up preferences.
- The heating Boost feature adds the Boost Temperature Increment to either the current room temperature or to the current / next Comfort Period target temperature, whichever is higher.
- In the unlikely event that the Room Sensor or Tank Sensor loses knowledge of the correct date and time, then the heating / hot water will continue to operate however it is likely to be out of step with the actual current day and time. This will continue until such a time as the date and time information can be downloaded from the OWL servers again. This could occur if the Network OWL is not connected to the Internet after the batteries have been replaced. If this occurs, use the Comfort and Standby buttons to manually bring the heating on / off until the Internet connection is restored to the Network OWL.
- If the Room Sensor or Tank Sensor batteries are allowed to get too low, then the heating / hot water will no longer be able to switch on. This could be a risk for elderly and infirm householders. Please ensure batteries are replaced as soon as possible after the warning messages are given.
- In order to ensure long battery life, the Room Sensor and Tank Sensor only communicates over the radio link to the Network OWL once every time period as shown in the table below. This means that it can take a while for web dashboard or smart phone instigated commands, such as clicking on the Comfort icon, to take effect. This is normal operation. Button presses on the actual Room Sensor or Tank Sensor will respond immediately.

Room Sensor / Tank Sensor Radio Update Rate

Mode	**Update Rate**	**Units**
Comfort Period / Running	33	Seconds
Standby	63	Seconds
Away / Holiday / Summer	303	Seconds

After the initial potentially slow response, the Room Sensor or Tank Sensor will remain “ready for action” for the following 2 minutes. Web dashboard commands during this period should take effect within 10 seconds.

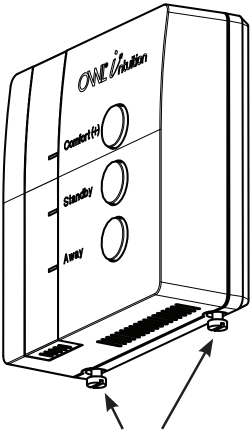
11. Battery Replacement

The Room Sensor and Tank Sensor both run on 2 x AAA size Alkaline non rechargeable batteries and depending upon usage are designed to give a battery life of approximately 12 to 18 months.

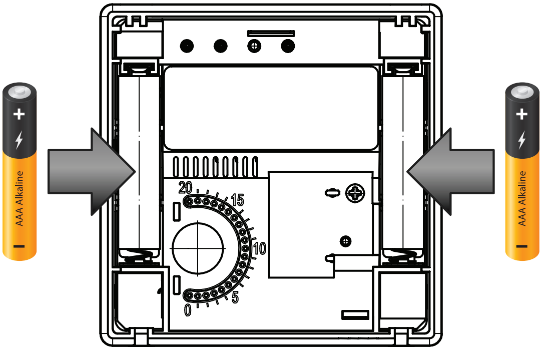
Through the OWL Intuition web dashboard you can see the current battery level for the Room Sensor and Tank Sensor at any time. When the batteries are nearing the end of their life the battery symbol will turn red and you will be sent an email warning you to replace the batteries - this email will be sent every 7 days until the batteries are replaced. Please ensure your email address is always correctly set within the Intuition web dashboard - update using the System menu if required. As a final warning the Away LED or More H/W LED will start to flash on/off every second. When you see any of these warnings you should replace the batteries as soon as possible.

To change the batteries it is necessary to remove the Room Sensor / Tank Sensor from the wall.

1. Undo the two captive screws at the base of the Room Sensor / Tank Sensor and swing it out at the bottom then up and away from the backplate.
2. Remove the old batteries and replace them with two new high quality, high capacity AAA size Alkaline batteries, ensuring that they are fitted correctly as indicated by the diagram below. Note they both face in the same direction.

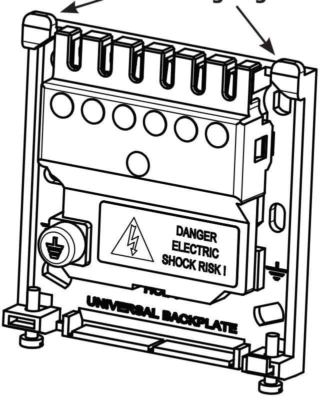


Captive Screws



3. Once the batteries are fitted, re-fit the Room Sensor / Tank Sensor to the backplate by engaging with the lugs at the top of the backplate, then carefully swing the device down and push it carefully back into its plug-in terminal connectors. Locate over the captive screws at the base of the backplate and tighten them so that the device is locked into position.
4. Login to the OWL Intuition web dashboard and check that the battery level indicator is now fully green (100%).
5. **IMPORTANT: If the batteries are allowed to get too low the heating / hot water will no longer be able to switch on. This could be a risk for elderly and infirm householders.**

Locating Lugs



Customer Support

If you have any further questions please check our frequently asked questions at:
https://theowl.zendesk.com
You can also email us at: **customer.services@theowl.com**
(please ensure you state your Network OWL MAC ID)

2 Save Energy Limited operate a policy of continuous development and improvement, therefore the content of this document is subject to change without notice.

Appendix E. Pre- and Post-Retrofit Survey Document Used on Residential Building Householders

MULHADDART PRE-WORKS QUESTIONNAIRE – 4th February 2015

☐ **House No**

1) Gender?

Male	Female

2) House type?

Detached	Semi-detached	Mid terrace	End terrace	Bungalow

3) Number of bedrooms?

Two bedroom	Three bedroom	Four bedroom

4) Number of rooms in the house (excluding bathrooms)? ______________

5) Number of bathrooms in the house? ______________

6) How many years have you lived in the house?

0-1 year	2-5 years	6-9 years	10 or more

7) How many male (M) and female (FM) currently live in your household (including yourself) and how old are they? *(e.g. write '2' in Box 18-25 under M if there are two males aged 18-25 living in the household etc.)*

Under 14		14 – 17		18 – 25		26 – 35		36 – 45		46 - 55		56 - 64		65 - 74		75+	
M	FM	M	FM	M	FM	M	FM	M	FM	M	FM	M	FM	M	FM	M	FM

8) Are you the Head of the Household*?

Yes	No

* The *Head of Household* is a person designated by the household itself.

9) **How would you describe the *Head of Household*'s* present status?** *(Please circle)*

Professional	Service industry	Looking after the home	Managerial
Technical	Manual	Farmer	Government/civil service
Unemployed	Self employed	Student	Retired
Other (specify)			

10) **How would you describe other adult(s) residing in this house's present status?** *(Please tick appropriate number of boxes in each category, one box represents one adult)*

Professional				Service industry				Looking after the home				Managerial			
Technical				Manual				Farmer				Government/civil service			
Unemployed				Self employed				Student				Retired			
Other (specify)				______________				______________				______________			

11a) On an average weekday, when is there someone present in your house? *Please mark the hours on the scale below.*

08:00-09:00		09:00-10:00		10:00-11:00		11:00-12:00		12:00-13:00		13:00-14:00	
14:00-15:00		15:00-16:00		16:00-17:00		17:00-18:00		18:00-19:00		19:00-20:00	
20:00-21:00		21:00-22:00		22:00-23:00		23:00-24:00		00:00-01:00		01:00-02:00	
02:00-03:00		03:00-04:00		04:00-05:00		05:00-06:00		06:00-07:00		07:00-08:00	

11b) On an average weekend day (Saturday/Sunday), when is there someone present in your house? *Please mark the hours on the scale below.*

08:00-09:00		09:00-10:00		10:00-11:00		11:00-12:00		12:00-13:00		13:00-14:00	
14:00-15:00		15:00-16:00		16:00-17:00		17:00-18:00		18:00-19:00		19:00-20:00	
20:00-21:00		21:00-22:00		22:00-23:00		23:00-24:00		00:00-01:00		01:00-02:00	
02:00-03:00		03:00-04:00		04:00-05:00		05:00-06:00		06:00-07:00		07:00-08:00	

12a) On an average weekday (April-October), when are the lights in your house turned on? *Please mark the hours on the scale below.*

08:00-09:00		09:00-10:00		10:00-11:00		11:00-12:00		12:00-13:00		13:00-14:00	
14:00-15:00		15:00-16:00		16:00-17:00		17:00-18:00		18:00-19:00		19:00-20:00	
20:00-21:00		21:00-22:00		22:00-23:00		23:00-24:00		00:00-01:00		01:00-02:00	
02:00-03:00		03:00-04:00		04:00-05:00		05:00-06:00		06:00-07:00		07:00-08:00	

12b) On an average weekend day (April-October), when are the lights in your house turned on? *Please mark the hours on the scale below.*

08:00-09:00		09:00-10:00		10:00-11:00		11:00-12:00		12:00-13:00		13:00-14:00	
14:00-15:00		15:00-16:00		16:00-17:00		17:00-18:00		18:00-19:00		19:00-20:00	
20:00-21:00		21:00-22:00		22:00-23:00		23:00-24:00		00:00-01:00		01:00-02:00	
02:00-03:00		03:00-04:00		04:00-05:00		05:00-06:00		06:00-07:00		07:00-08:00	

13a) On an average weekday (November-March), when are the lights in your house turned on? *Please mark the hours on the scale below.*

08:00-09:00		09:00-10:00		10:00-11:00		11:00-12:00		12:00-13:00		13:00-14:00	
14:00-15:00		15:00-16:00		16:00-17:00		17:00-18:00		18:00-19:00		19:00-20:00	
20:00-21:00		21:00-22:00		22:00-23:00		23:00-24:00		00:00-01:00		01:00-02:00	
02:00-03:00		03:00-04:00		04:00-05:00		05:00-06:00		06:00-07:00		07:00-08:00	

13b) On an average weekend day (November-March), when are the lights in your house turned on? *Please mark the hours on the scale below.*

08:00-09:00		09:00-10:00		10:00-11:00		11:00-12:00		12:00-13:00		13:00-14:00	
14:00-15:00		15:00-16:00		16:00-17:00		17:00-18:00		18:00-19:00		19:00-20:00	
20:00-21:00		21:00-22:00		22:00-23:00		23:00-24:00		00:00-01:00		01:00-02:00	
02:00-03:00		03:00-04:00		04:00-05:00		05:00-06:00		06:00-07:00		07:00-08:00	

14) In general, how would you rate the warmth of your house (i.e. your thermal comfort satisfaction with your house)?

Very satisfied	Generally satisfied	Neither satisfied or dissatisfied	Generally Dissatisfied	Very Dissatisfied

15) How would you rate the internal temperature and level of comfort in your house during the winter months?

	Much too cold	Too cool	Comfortably cool	Comfortable	Comfortably warm	Too warm	Much too hot
Mornings							
Evenings							

16) How often would these typical clothing ensembles be worn by people in the house? *Please tick appropriately*

	Regularly (daily)	**Often (a few times a week)**	**Rarely (a few times a month)**	**Never**
Light trousers/skirt, dress with short sleeved short/blouse or light jumper				
Long sleeved jumper/cardigan with medium weight trousers				
Heavy jumper/jacket, thick trousers/dress or thermals with medium weight clothing				
Outdoor/heavy clothes with thermals or extra layers of thick clothing				

17) Have you done any of the following during the past month? *(Please select only one option per line)*

	Yes	**No**	**Don't know**
1. Cut down on water consumption			
2. Cut down on energy use			
3. Purchased energy efficient appliances			
4. Shopped or paid a bill online			
5. Avoid products with excessive packaging			
6. Bought reusable consumer goods instead of disposable products i.e. reusable nappies			
7. Bought organic food			
8. Walked, cycled or used public transport instead of driving			
9. Used second-hand /repaired items rather than purchased new ones- clothes, shopping bags.			

***18)* In your opinion, which of the following would encourage people the most to save energy?** *(Tick one option only)*

Financial incentives and grants	
Lower utility bills	
Information/ environmental campaigns on why and how to save energy	
Better labelling on appliances	
Support from family, friends, community	
None of the above	

***19)* Please indicate whether you agree or disagree with the following statements.** *(Please tick one appropriate box in each line)*

	Strongly agree	**Agree**	**Neither agree nor disagree**	**Disagree**	**Strongly disagree**
1. I'm willing to sacrifice some comfort to save energy.					
2. Everybody has the right to use natural resources according to their demand.					
3. I like people to think of me as being environmentally friendly.					
4. I feel guilty when I use a lot of energy.					
5. Owning a big house is very important goal in my life.					
6. As a society we will need to consume a lot less to help protect the environment for future generations.					
7. I feel morally obliged to reduce my energy use, regardless of what other people do.					
8. It is important to me that using less energy lowers utility bills.					
9. My quality of life will decrease when I reduce my energy use.					
10. It takes up too much of my time to reduce energy use.					

20) Which of the following actions have you taken within the last 5 years? *(Please tick one appropriate box in each line)*

Actions	**If yes please refer to Q21**	**No**	**Don't know**
1. Installed / upgraded insulation in home (e.g. lagging jacket, cavity wall insulation, double glazing)			
2. Availed of grant / subsidy programmes to retrofit your home			
3. Installed energy controls (e.g. energy meter or radiator controls)			
4. Installed water reducing device / system (e.g. water-butt, grey water system)			
5. Switched to an energy supplier providing larger amounts of energy from renewable sources			
6. Installed equipment in your own home that generates renewable energy			
7. Had an energy audit			
8. Purchased an energy efficient car (Hybrid/ smaller engine/electric)			

***21)* If yes to Q20, then what was the reason for carrying out this action?** *(Please tick one reason for each action)*

Reason/Action	**1**	**2**	**3**	**4**	**5**	**6**	**7**
I wanted to be more eco friendly							
I wanted to save money							
I was given a grant to implement behaviour							
My neighbours/friends have done this							
Increase the value of my home							
Improve my thermal comfort							

***22)* If you have not invested in improving the energy efficiency of your house, what were the reasons?** *(Please tick one reason for each action)*

Reason/Action	**1**	**2**	**3**	**4**	**5**	**6**	**7**
High investment cost							
Long payback times							
No motivation in reducing energy bills							
Difficulty in quantifying energy savings							
Lack of knowledge in technology							
Lack of awareness of benefits							
Lack of trust in technology							
Lack of trust in the workforce							
Disturbance of home for works							

22) **If you had only one choice, which energy saving measure would you choose?** *Please rank in order of choice*

Cavity Wall Insulation	
Internal Wall Insulation	
External Wall Insulation	
Attic Insulation	
Floor Insulation	
Windows	
Doors	
Lighting with motion sensors	
Boiler upgrade	
District heating system	
Solar Panels/ Photovoltaic Panels	
Mini wind turbine	

25) What is your estimated annual spending on the following energy consumption fuels for heating and power to your home?

	Estimated annual spending (€)
Renewables	
Heating Oil	
Natural Gas	
Electricity	
Coal	
Peat	
Briquettes	
Biomass (e.g. Firewood)	
Other______	

26) How often does your household use central heating devices?

	Regularly (daily)	**Often (a few times a week)**	**Rarely (a few times a month)**	**Never**
Use of central heating during winter (October – March)				
Use of central heating rest of year (April – September)				

27) Heading questions

Is there a timer function on the central heating?	**Yes**	**No**	**I don't know**
Is there a thermostat on the heating?	**Yes**	**No**	**I don't know**
What are the heating control time settings?			
What is the thermostat temperature set to?			
Is there radiator TRVs*?	**Yes**	**No**	**I don't know**
Have you used any portable electrical radiators within the past week?	**Yes**	**No**	**I don't know**
If so, on how many occasions and in which rooms, approximately for What length of time? Which rooms?			

**A TRV (thermostatic radiator valve) is a self-regulating valve fitted to hot water heating system radiators*

28) What is your primary solid fuel type? *(Please tick the appropriate box)*

Turf	Briquettes	Timber	Coal	Other

29) How many bags of solid fuel (turf/coal/briquettes/timber) would you burn per day/week during the heating season on average? *(Please tick the appropriate box)*

	Less than 1	2-3	4-5	More than 5
Bags per day				
Bags per week				

30) How often does your household use the following devices? *(Please tick the appropriate)*

	Regularly (daily)	Often (a few times weekly)	Rarely (a few times a month)	Do not own
Dishwasher				
Washing Machine				
Tumble Dryer				
Electric Shower				
Power Shower				
Bath				

31) **How often do you use the following methods of water heating?** *(Tick the appropriate)*

	Regularly (every day)	**Often (a few times a week)**	**Rarely (a few times a month)**	**Never**
Boiler (October to April)				
Boiler (May to September)				
Immersion (October to April)				
Immersion (May to September)				

31) How often do you ventilate the house by opening windows/doors/vents? *(Tick the appropriate)*

Season	**Regularly (daily)**	**Often (a few times a week)**	**Rarely (a few times a month)**	**Never**
Spring				
Summer				
Autumn				
Winter				

33) What forms of ventilation are in the house at present? *(Tick the appropriate)*

Wall vents	**Window vents**	**Kitchen extractor**	**Bathroom extractor**

34) Are any of the existing vents closed or blocked up? ____________

35) Is there any evidence of mould or dampness? ____________

36) **How would you rate the level of noise from outside entering the house?**

Unnoticeable	Barely Noticeable	Noticeable	Very Noticeable	Unpleasantly Noticeable

37) **Do you have one of the following in your house? If so, then to what extent are these various household goods/appliances considered as a necessity or a luxury? How long are these powered/used daily?**

	Number	**Luxury/necessity**	**How long are these used/powered daily?**
Car (personal use)			
Bicycle			
Vans/Minibuses			
Motorbikes/ scooters			
Dishwasher			
Washing machine			
Tumble dryer			
TV			
DVD			
Computer, laptop, tablet			
Games Console			
Mobile phone			
Fridge/freezer			
Microwave			
Electric cooker (grill, oven)			
Electric toothbrush			
Electric shower, power shower			
Bath			
Other			

38) **What benefits do you hope to see as a result of the retrofit upgrades?** *(Please rate in order of priority 1-3)*

Reduce your energy bills	
Increase in the comfort level of your home	
Improve the environment	
Other (please state)	

39) Any other concerns/comments you have about the thermal comfort of your house?

40) What is the approximate disposable annual income for your house? (*See attached notes page as a calculation aid*) €________

Disposable household annual income

The following will aid in estimating the household disposable annual income. Income details are collected at both a household and individual level. In analysis, each individual's income is summed up to household level and in turn added to household level income components to calculate gross household income.

HEAD OF HOUSEHOLD

Gross income: €______________

The components of gross household income are:

Direct Income: €______________

Employee income:

Gross employee cash or near cash income €______________

Gross non-cash employee income €______________

Employer's social insurance contributions €______________

Gross cash benefits or losses from self-employment €______________

Other direct income: €______________

- Value of goods produced for own consumption €______________
- Pension from individual private plans €______________
- Income from rental of property or land €______________
- Regular inter-household cash transfers received €______________
- Interests, dividends, profit from capital investments in unincorporated business €______________
- Income received by people aged under 16 €______________

Social Transfers: €______________

Unemployment related payments €______________

Old-age related payments €______________

Family/children related allowances: €______________

- Maternity/adoptive benefit €______________
- Child benefit €______________
- Single parent allowances €______________
- Carers' benefit €______________
- Housing allowances: €______________
    - Rent supplement €______________
    - Free phone/electricity etc €______________
    - Fuel allowances €______________
- Exceptional needs payment €______________

Other social transfers: €______________

- Survivors' benefits €______________
- Sickness benefits €______________
- Disability benefits €______________
- Education-related allowances €______________
- Social exclusion not elsewhere classified €______________

Disposable income €______________

Tax and social insurance contributions are also summed to household level and subtracted from the gross household income to calculate the *total disposable household income*. The components of disposable household income are gross household income *less*:

- Employer's social insurance contributions €______________
- Regular inter-household cash transfer paid €______________
- Tax on income and social insurance contributions €______________

Disposable household annual income

The following will aid in estimating the household disposable annual income. Income details are collected at both a household and individual level. In analysis, each individual's income is summed up to household level and in turn added to household level income components to calculate gross household income.

ADULT OTHER THAN HEAD OF HOUSEHOLD

Gross income: **€______________**

The components of gross household income are:

Direct Income: **€______________**

Employee income:

Gross employee cash or near cash income €______________

Gross non-cash employee income €______________

Employer's social insurance contributions €______________

Gross cash benefits or losses from self-employment €______________

Other direct income: **€______________**

- Value of goods produced for own consumption €______________
- Pension from individual private plans €______________
- Income from rental of property or land €______________
- Regular inter-household cash transfers received €______________
- Interests, dividends, profit from capital investments in unincorporated business €______________
- Income received by people aged under 16 €______________

Social Transfers: **€______________**

Unemployment related payments €______________

Old-age related payments €______________

Family/children related allowances: €______________

- Maternity/adoptive benefit €______________
- Child benefit €______________
- Single parent allowances €______________
- Carers' benefit €______________
- Housing allowances: €______________
    - Rent supplement €______________
    - Free phone/electricity etc €______________
    - Fuel allowances €______________
- Exceptional needs payment €______________

Other social transfers: **€______________**

- Survivors' benefits €______________
- Sickness benefits €______________
- Disability benefits €______________
- Education-related allowances €______________
- Social exclusion not elsewhere classified €______________

Disposable income **€______________**

Tax and social insurance contributions are also summed to household level and subtracted from the gross household income to calculate the *total disposable household income*. The components of disposable household income are gross household income *less*:

- Employer's social insurance contributions €______________
- Regular inter-household cash transfer paid €______________
- Tax on income and social insurance contributions €______________

MULHUDDART POST-WORKS QUESTIONNAIRE

House Number: _____________ **Date: ________________**

1) **Gender?**

Male	Female

2) **How many male (M) and female (FM) currently live in your household (including yourself) and how old are they?** *(e.g. write '2' in Box 18-25 under M if there are two males aged 18-25 living in the household etc.)*

Under 13		13 – 17		18 – 25		26 – 35		36 – 45		46 - 55		56 - 64		65 - 74		75+	
M	FM	M	FM	M	FM	M	FM	M	FM	M	FM	M	FM	M	FM	M	FM

3) **Are you the Head of the Household*?**

Yes	No

* The *Head of Household* is a person designated by the household itself.

4) **How would you describe the *Head of Household*'s* present status?** *(Please circle)*

Professional	Service industry	Looking after the home	Managerial
Technical	Manual	Farmer	Government/civil service
Unemployed	Self employed	Student	Retired
Other (specify)			

5) **How would you describe other adult(s) residing in this house's present status?** *(Please tick appropriate number of boxes in each category, one box represents one adult)*

Professional				Service industry				Looking after the home				Managerial			
Technical				Manual				Farmer				Government/civil service			
Unemployed				Self employed				Student				Retired			
Other (specify)				______________				_______________				_______________			

6) **On an average weekday, when is there someone present in your house?** *Please mark the hours on the scale below.*

08:00-09:00		09:00-10:00		10:00-11:00		11:00-12:00		12:00-13:00		13:00-14:00	
14:00-15:00		15:00-16:00		16:00-17:00		17:00-18:00		18:00-19:00		19:00-20:00	
20:00-21:00		21:00-22:00		22:00-23:00		23:00-24:00		00:00-01:00		01:00-02:00	
02:00-03:00		03:00-04:00		04:00-05:00		05:00-06:00		06:00-07:00		07:00-08:00	

7) **On an average weekend day (Saturday/Sunday), when is there someone present in your house?** *Please mark the hours on the scale below.*

08:00-09:00		09:00-10:00		10:00-11:00		11:00-12:00		12:00-13:00		13:00-14:00	
14:00-15:00		15:00-16:00		16:00-17:00		17:00-18:00		18:00-19:00		19:00-20:00	
20:00-21:00		21:00-22:00		22:00-23:00		23:00-24:00		00:00-01:00		01:00-02:00	
02:00-03:00		03:00-04:00		04:00-05:00		05:00-06:00		06:00-07:00		07:00-08:00	

8) **On an average weekday (April-October), when are the lights in your house turned on?** *Please mark the hours on the scale below.*

08:00-09:00		09:00-10:00		10:00-11:00		11:00-12:00		12:00-13:00		13:00-14:00	
14:00-15:00		15:00-16:00		16:00-17:00		17:00-18:00		18:00-19:00		19:00-20:00	
20:00-21:00		21:00-22:00		22:00-23:00		23:00-24:00		00:00-01:00		01:00-02:00	
02:00-03:00		03:00-04:00		04:00-05:00		05:00-06:00		06:00-07:00		07:00-08:00	

9) **On an average weekend day (April-October), when are the lights in your house turned on?** *Please mark the hours on the scale below.*

08:00-09:00		09:00-10:00		10:00-11:00		11:00-12:00		12:00-13:00		13:00-14:00	
14:00-15:00		15:00-16:00		16:00-17:00		17:00-18:00		18:00-19:00		19:00-20:00	
20:00-21:00		21:00-22:00		22:00-23:00		23:00-24:00		00:00-01:00		01:00-02:00	
02:00-03:00		03:00-04:00		04:00-05:00		05:00-06:00		06:00-07:00		07:00-08:00	

10) **On an average weekday (November-March), when are the lights in your house turned on?** *Please mark the hours on the scale below.*

08:00-09:00		09:00-10:00		10:00-11:00		11:00-12:00		12:00-13:00		13:00-14:00	
14:00-15:00		15:00-16:00		16:00-17:00		17:00-18:00		18:00-19:00		19:00-20:00	
20:00-21:00		21:00-22:00		22:00-23:00		23:00-24:00		00:00-01:00		01:00-02:00	
02:00-03:00		03:00-04:00		04:00-05:00		05:00-06:00		06:00-07:00		07:00-08:00	

11) **On an average weekend day (November-March), when are the lights in your house turned on?** *Please mark the hours on the scale below.*

08:00-09:00		09:00-10:00		10:00-11:00		11:00-12:00		12:00-13:00		13:00-14:00	
14:00-15:00		15:00-16:00		16:00-17:00		17:00-18:00		18:00-19:00		19:00-20:00	
20:00-21:00		21:00-22:00		22:00-23:00		23:00-24:00		00:00-01:00		01:00-02:00	
02:00-03:00		03:00-04:00		04:00-05:00		05:00-06:00		06:00-07:00		07:00-08:00	

12) **In general, how would you rate the warmth of your house (i.e. your thermal comfort satisfaction with your house)?**

Very satisfied	Generally satisfied	Neither satisfied or dissatisfied	Generally Dissatisfied	Very Dissatisfied

13) **How would you rate the internal temperature and level of comfort in your house during the winter months?**

	Much too cold	Too cool	Comfortably cool	Comfortable	Comfortably warm	Too warm	Much too hot
Mornings							
Evenings							

14) **Do you feel the upgrade works are of thermal comfort benefit to you?**

Yes	**No**	**Undecided/Don't know**	**Comment**

15) **Have you experienced any of the following problems in the house?** (*Please tick appropriately)*

	Regularly (daily)	**Often (a few times a week)**	**Rarely (a few times a month)**	**Never**
Problem	**Winter**			
Draught(s)				
Cold				
Condensation				
Mould				
Damp				
Other. Please detail:				
Problem	**Summer**			
Draught(s)				
Cold				
Condensation				
Mould				
Damp				
Other. Please detail:				

16) **What does comfort in the home mean to you?** (Please choose three options and rank choices on a scale of 1-3)

Cleanliness		Peace & quietness	
Feeling of Ownership		Privacy	
Having enough space		Security	
Having lots of light		Warmth	
Having the right facilities		Other (please state)	

17) **How often would these typical clothing ensembles be worn by people in the house?** (*Please tick appropriately)*

	Regularly (daily)	**Often (a few times a week)**	**Rarely (a few times a month)**	**Never**
Clothing Ensemble	**Winter**			
Light trousers/skirt, dress with short sleeved short/blouse or light jumper				
Long sleeved jumper/cardigan with medium weight trousers				
Heavy jumper/jacket, thick trousers/dress or thermals with medium weight clothing				
Outdoor/heavy clothes with thermals or extra layers of thick clothing				
Other. Please detail:				
Clothing Ensemble	**Summer**			
Light trousers/skirt, dress with short sleeved short/blouse or light jumper				
Long sleeved jumper/cardigan with medium weight trousers				
Heavy jumper/jacket, thick trousers/dress or thermals with medium weight clothing				
Outdoor/heavy clothes with thermals or extra layers of thick clothing				
Other. Please detail:				

18) **Have you done any of the following during the past month/year?** *(Please select only one option per line)*

	Month			**Year**		
	Yes	**No**	**Don't know**	**Yes**	**No**	**Don't know**
1. Cut down on water consumption						
2. Cut down on energy use						
3. Purchased energy efficient appliances						
4. Shopped or paid a bill online						
5. Avoid products with excessive packaging						
6. Bought reusable consumer goods instead of disposable products i.e. reusable nappies						
7. Bought organic food						
8. Walked, cycled or used public transport instead of driving						
9. Used second-hand /repaired items rather than purchased new ones- clothes, shopping bags.						

10. Recycle home waste						
11. Turn off lights in unoccupied rooms						
12. Turn off unused electrical appliances when not in use						
13. Wash clothes at lower temperature setting in washing machine						
14. Heat only rooms that are occupied when central heating is turned on						
15.Turn down heating to reduce house temperature						

19) In your opinion, which of the following would encourage people the most to save energy? *(Tick one option only)*

Financial incentives and grants	
Lower utility bills	
Information/ environmental campaigns on why and how to save energy	
Better labelling on appliances	
Support from family, friends, community	
None of the above	

20) Please indicate whether you agree or disagree with the following statements. *(Please tick one appropriate box in each line)*

	Strongly agree	**Agree**	**Neither agree nor disagree**	**Disagree**	**Strongly disagree**
1. I'm willing to sacrifice some comfort to save energy.					
2. Everybody has the right to use natural resources according to their demand.					
3. I like people to think of me as being environmentally friendly.					
4. I feel guilty when I use a lot of energy.					
5. Owning a big house is very important goal in my life.					
6. As a society we will need to consume a lot less to help protect the environment for future generations.					
7. I feel morally obliged to reduce my energy use, regardless of what other people do.					
8. It is important to me that using less energy lowers utility bills.					
9. My quality of life will decrease when I reduce my energy use.					
10. It takes up too much of my time to reduce energy use.					

21) In general, how would you rate the quality of the workmanship associated with the upgrade works of your house?

Very satisfied	Generally satisfied	Neither satisfied or dissatisfied	Generally Dissatisfied	Very Dissatisfied

Comment

22) Are you satisfied with the technologies/upgrades installed in your house?

Yes	**No**	**Don’t know**	**Comment?**

23) If you were able to install more energy saving measures on your house, which energy saving measure would you choose?

Comment

24) What benefits do you hope to see as a result of the retrofit upgrades? *(Please rate in order of priority 1-3)*

Improve the environment	
Increase in the comfort level of your home	
Reduce your energy bills	
Other (please state)	

25) Do you see any noticeable savings in terms of money spent on energy (e.g. solid fuel, oil, etc...) since the completion of the upgrade works?

Yes	No	Comment?

26) What is your estimated annual spending on the following energy consumption fuels for heating and power to your home?

	Estimated annual spending (€)
Renewables	
Heating Oil	
Natural Gas	
Electricity	
Coal	
Peat	
Briquettes	
Biomass (e.g. Firewood)	
Other______	

27) From where/whom do you obtain your energy fuel supply? (Include tariff/prices where possible)

	Energy Supplier	**Local Shop/Business**	**Self-Supplied**	**Other**
Renewables				
Heating Oil				
Natural Gas				
Electricity				
Coal				
Peat				
Briquettes				
Biomass (e.g. Firewood)				
Other______				

28) How often does your household use central heating devices?

	Regularly (daily)	**Often (a few times a week)**	**Rarely (a few times a month)**	**Never**
Use of central heating during winter (October – March)				
Use of central heating rest of year (April – September)				

29) Heating questions

Is there a timer function on the central heating?	**Yes**	**No**	**I don't know**
Is there a thermostat on the heating?	**Yes**	**No**	**I don't know**
What are the heating control time settings?			
What is the thermostat temperature set to?			
Is there radiator TRVs*?	**Yes**	**No**	**I don't know**
Have you used any portable electrical radiators within the past week?	**Yes**	**No**	**I don't know**
If so, on how many occasions and in which rooms, approximately for What length of time? Which rooms?			
Do you keep windows closed when the heating is turned on			

**A TRV (thermostatic radiator valve) is a self-regulating valve fitted to hot water heating system radiators*

30) What are the radiators settings when central heating is turned on? Please comment

They are on at the same level in all rooms throughout the heating period	
They are on at different levels in different rooms but are not changed	
I vary the setting with the TRV depending on how warm I need the room to be	
I vary the settings in some rooms but leave them in constant in other rooms	
Other. Please detail.	

31) What is your primary solid fuel type? *(Please tick the appropriate box)*

Turf	Briquettes	Timber	Coal	Other

32) How many bags of solid fuel (turf/coal/briquettes/timber) would you burn per day/week during the heating season on average? *(Please tick the appropriate box)*

	Less than 1	2-3	4-5	More than 5
Bags per day				
Bags per week				

33) How often does your household use the following devices? *(Please tick the appropriate)*

	Regularly (daily)	Often (a few times weekly)	Rarely (a few times a month)	Do not own
Dishwasher				
Washing Machine				
Tumble Dryer				
Electric Shower				
Power Shower				
Bath				

34) How often do you use the following methods of water heating? *(Tick the appropriate)*

	Regularly (every day)	Often (a few times a week)	Rarely (a few times a month)	Never
Boiler (October to April)				
Boiler (May to September)				
Immersion (October to April)				
Immersion (May to September)				

35) How often do you ventilate the house by opening windows/doors/vents? *(Tick the appropriate)*

Season	Regularly (daily)	Often (a few times a week)	Rarely (a few times a month)	Never
Spring				
Summer				
Autumn				
Winter				

36) For what reasons do you limit ventilation to your house by opening windows/doors/vents? (*Please tick appropriately)*

Reason	**Winter**
Concern of losing internal warmth to outside	
Security concerns of leaving window open while in/not in house	
Do not have the time	
Discomfort from draughts	
Forget to ventilate	
Not necessary	
Other. Please detail:	
Reason	**Summer**
Concern of losing internal warmth to outside	
Security concerns of leaving window open while in/not in house	
Do not have the time	
Discomfort from draughts	
Forget to ventilate	
Not necessary	
Other. Please detail:	

37) What forms of ventilation are in the house at present? *(Tick the appropriate)*

Wall vents	**Window vents**	**Kitchen extractor**	**Bathroom extractor**

38) Are any of the existing vents closed or blocked up? ___________

39) Is there any evidence of mould or dampness? ___________

40) How would you rate the level of noise from outside entering the house?

Unnoticeable	Barely Noticeable	Noticeable	Very Noticeable	Unpleasantly Noticeable

41) **What benefits do you see as a result of the attic and wall insulation upgrade work (please rate in order of priority 1-3)?**

Improve the environment	
Increase in the comfort level of your home	
Reduce your energy bills	
Other (please state)	

42) **Do you have one of the following in your house? If so, then to what extent are these various household goods/appliances considered as a necessity or a luxury? How long are these powered/used daily?**

	Number	**Luxury/necessity**	**How long are these used/powered daily?**
Car (personal use)			
Bicycle			
Vans/Minibuses			
Motorbikes/ scooters			
Kettle			
Toaster			
Dishwasher			
Washing machine			
Tumble dryer			
TV			
DVD			
Computer, laptop, tablet			
Games Console			
Mobile phone			
Fridge/freezer			
Microwave			
Electric cooker (grill, oven)			
Electric toothbrush			
Electric shower, power shower			
Bath			
Other			

43) **Which factor has the biggest impact when deciding on which appliance to purchase?** (Please select one option)

Cost	Energy Rating	Aesthetics	Manufacturer	Friends and Family	Other. Please detail

44) **Any other concerns/comments you have about the thermal comfort of your house?**

45) **What is the approximate disposable annual income for your house?** (*See attached notes page as a calculation aid*) €________

Disposable household annual income

The following will aid in estimating the household disposable annual income. Income details are collected at both a household and individual level. In analysis, each individual's income is summed up to household level and in turn added to household level income components to calculate gross household income.

HEAD OF HOUSEHOLD

Gross income: **€______________**

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 Gross non-cash employee income €______________
Employer's social insurance contributions €______________
Gross cash benefits or losses from self-employment €______________

Other direct income: **€______________**

- Value of goods produced for own consumption €______________
- Pension from individual private plans €______________
- Income from rental of property or land €______________
- Regular inter-household cash transfers received €______________
- Interests, dividends, profit from capital investments in unincorporated business €______________
- Income received by people aged under 16 €______________

Social Transfers: **€______________**

Unemployment related payments €______________
Old-age related payments €______________
Family/children related allowances: €______________

- Maternity/adoptive benefit €______________
- Child benefit €______________
- Single parent allowances €______________
- Carers' benefit €______________
- Housing allowances: €______________
    - Rent supplement €______________
    - Free phone/electricity etc €______________
    - Fuel allowances €______________
- Exceptional needs payment €______________

Other social transfers: **€______________**

- Survivors' benefits €______________
- Sickness benefits €______________
- Disability benefits €______________
- Education-related allowances €______________
- Social exclusion not elsewhere classified €______________

Disposable income **€______________**

Tax and social insurance contributions are also summed to household level and subtracted from the gross household income to calculate the *total disposable household income*. The components of disposable household income are gross household income *less*:

- Employer's social insurance contributions €______________
- Regular inter-household cash transfer paid €______________
- Tax on income and social insurance contributions €______________

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Disposable household annual income

The following will aid in estimating the household disposable annual income. Income details are collected at both a household and individual level. In analysis, each individual's income is summed up to household level and in turn added to household level income components to calculate gross household income.

ADULT OTHER THAN HEAD OF HOUSEHOLD

Gross income: **€______________**

The components of gross household income are:

Direct Income: **€______________**

Employee income:

Gross employee cash or near cash income €______________

Gross non-cash employee income €______________

Employer's social insurance contributions €______________

Gross cash benefits or losses from self-employment €______________

Other direct income: **€______________**

- Value of goods produced for own consumption €______________
- Pension from individual private plans €______________
- Income from rental of property or land €______________
- Regular inter-household cash transfers received €______________
- Interests, dividends, profit from capital investments in unincorporated business €______________
- Income received by people aged under 16 €______________

Social Transfers: **€______________**

Unemployment related payments €______________

Old-age related payments €______________

Family/children related allowances: €______________

- Maternity/adoptive benefit €______________
- Child benefit €______________
- Single parent allowances €______________
- Carers' benefit €______________
- Housing allowances: €______________
    - Rent supplement €______________
    - Free phone/electricity etc €______________
    - Fuel allowances €______________
- Exceptional needs payment €______________

Other social transfers: **€______________**

- Survivors' benefits €______________
- Sickness benefits €______________
- Disability benefits €______________
- Education-related allowances €______________
- Social exclusion not elsewhere classified €______________

Disposable income **€______________**

Tax and social insurance contributions are also summed to household level and subtracted from the gross household income to calculate the *total disposable household income*. The components of disposable household income are gross household income *less*:

- Employer’s social insurance contributions €______________
- Regular inter-household cash transfer paid €______________
- Tax on income and social insurance contributions €______________

Appendix F. Indirect Energy Consumption Feedback Example

IT24

PIN

Home Heating Feedback

Thank you for your participation to date in the nZEB-RETROFIT research project. In this phase of the project, we will provide you with information to help you to save energy and reduce fuel spending.

Your house

- Your gas usage decreased by 2% in February 2016 compared to February 2015
- Meanwhile, the average temperature in your house increased by 1.5ºC
- Your kitchen is much warmer (22ºC) than other rooms in the house
- You told us that you are very satisfied with the temperature of the house, but that you would like to reduce energy consumption to lower your utility bills

Did you know?

- ➢ Lowering indoor temperature by 1ºC can cut space heating bills by 10% (SEAI)
- ➢ The recommended indoor temperature for efficiency and comfort is 18ºC (World Health Organisation)
- ➢ Setting the water heating thermostat to 60-65ºC can reduce energy losses (SEAI)
- ➢ Shortening your shower by 2 minutes can save up to 40L of hot water

Suggestions on how to use less energy in your home

- ✓ Lower your thermostat setting (while ensuring the house is well ventilated)
- ✓ Vary your TRV settings to turn down/switch off radiators in rooms that are not continuously used
- ✓ Check your water tank thermostat
- ✓ Try using extra blankets in the living room and bedrooms
- ✓ Try to reduce your showering time if at all possible
- ✓ Turn off water while brushing teeth, applying conditioner, shaving etc.

If you would like any further information, please contact:
Paul Moran, Department of Civil Engineering, NUI Galway
Email: p.moran3@nuigalway.ie | **Phone:** +353(0)91 493358

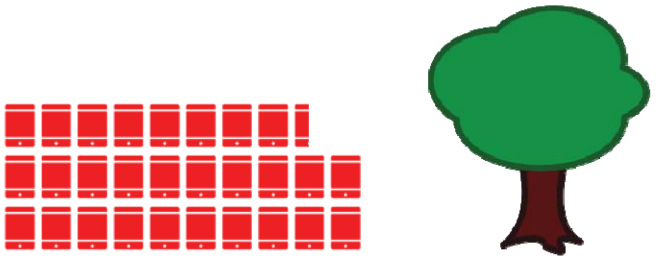
NUI Galway OÉ Gaillimh

Monthly Gas Usage and Internal Environment Report

VG31
PIN

Pre-Retrofit Period:
12th Feb 2015-13th Mar 2015

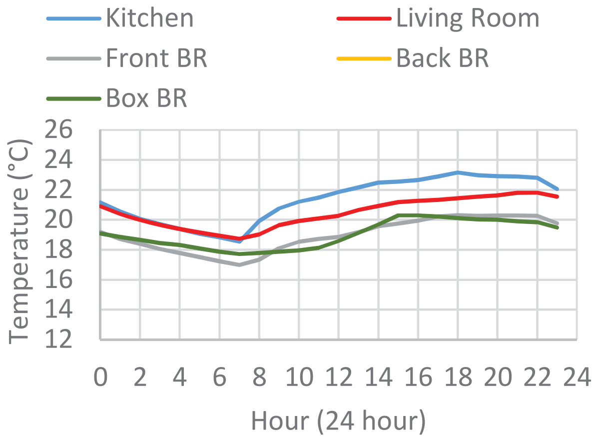
Monthly Gas Usage (Average Daily) and Trees Equivalent



57
kWh/Day

4.0
Trees Equivalent

Average Hourly Room Temperature (°C)



Average Daily Room Temperature (°C) and Relative Humidity (% RH)

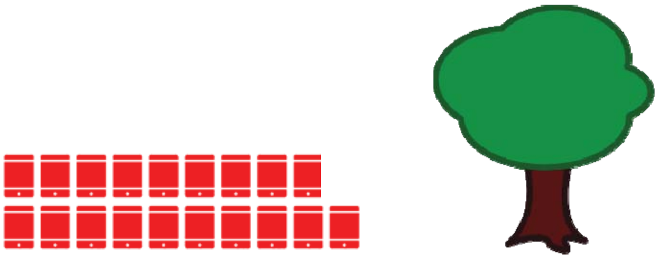
Kitchen	
21.3°C	42.6% RH
Living Room	
20.5°C	44.9% RH
Front BR	
19.0°C	50.9% RH
Back BR	
N/A	N/A% RH
Box BR	
19.0°C	52.8% RH
House	
19.9°C	**47.8% RH**

Monthly External Weather (Dublin Airport)

5.8 °C
82.0 %
21370 J/cm²
59.1 mm
7.3 m/s

Post-Retrofit Period:
13th Feb 2016-10th Mar 2016

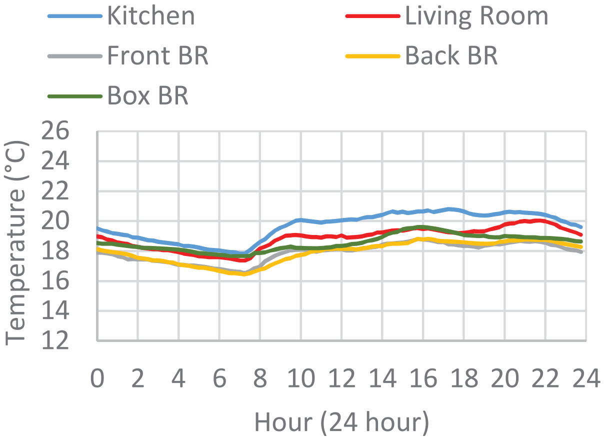
Monthly Gas Usage (Average Daily) and Trees Equivalent



38
kWh/Day
34%

2.5
Trees Equivalent

Average Hourly Room Temperature (°C)



Average Daily Room Temperature (°C) and Relative Humidity (% RH)

Kitchen	
19.7°C	42.3% RH
Living Room	
18.9°C	43.0% RH
Front BR	
17.9°C	52.8% RH
Back BR	
17.9°C	53.6% RH
Box BR	
18.5°C	18.5% RH
House	
18.7°C	**39.2% RH**
6%	18%

Monthly External Weather (Dublin Airport)

4.3 °C
81.4 %
20321 J/cm²
63.4 mm
6.0 m/s

nzeb
Retrofit

VF16

PIN

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Home Electricity Feedback

Thank you for your participation to date in the nZEB-RETROFIT research project. In this phase of the project, we will provide you with information to help you to save energy and reduce fuel spending.

Your house

- Your average daily electricity usage decreased by 14% during February-July 2016 compared to February-July 2015
- You told us that the lights are typically on for 13 hours during the average weekday in the summer
- You told us that you use a washing machine and a tumble dryer

Did you know?

- CFLs use 80% less electricity than ordinary light bulbs and last 10 times longer
- Appliances left on standby can use up to 20% of electricity use when fully on
- ‘A’ rated appliances use about 45% less electricity than ‘D’ rated appliances
- Reducing surplus water boiled by four cups a day can save 29 kWh per year
- Reducing the wash temperature from 60^{o}C to 40^{o}C can save 110 kWh per year
- Dryers are one of the most expensive appliances, using around 2.5 kW an hour

Suggestions on how to use less electricity in your home

- ✓ Use the OWL sensor to find out which appliances are using the most electricity
- ✓ Install energy-saving bulbs and turn off the lights when leaving a room
- ✓ Buy ‘A’ rating appliances and turn off appliances when not in use
- ✓ Only boil the required amount of water and keep lids on pots when cooking
- ✓ Wash clothes at a low temperature and wash full loads at a time
- ✓ When using the tumble dryer, separate heavy clothes from light clothes

If you would like any further information, please contact:
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Email: p.moran3@nuigalway.ie | **Phone:** +353(0)91 493358

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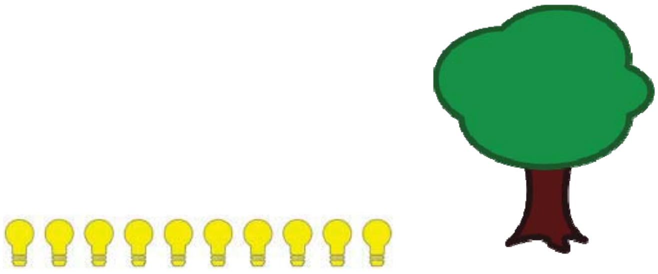
Monthly Electricity Usage Report

EJ42

PIN

Pre-Retrofit Period:
2nd Apr 2015-30th Apr 2015

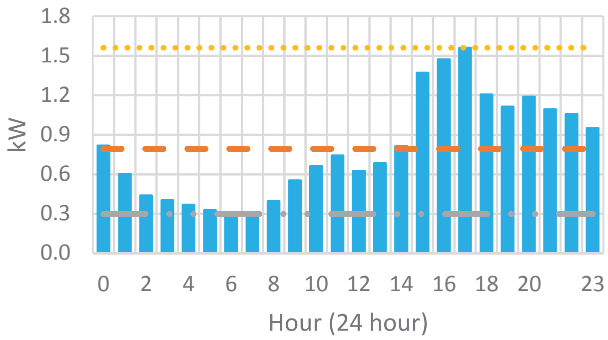
Monthly Electricity Usage (Average Daily) and Trees Equivalent



19.0
kWh/Day

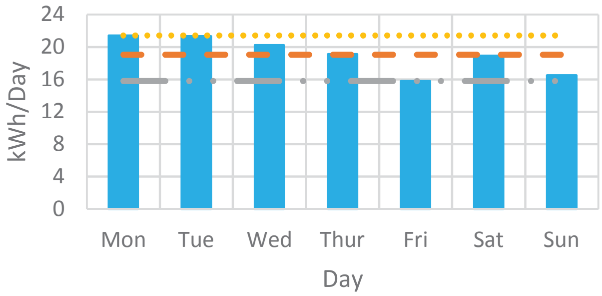
3.1
Trees Equivalent

Average Hourly Electricity Consumption



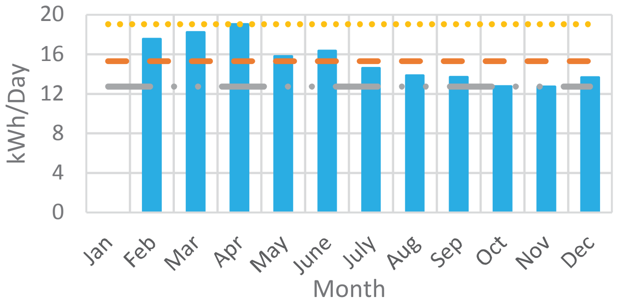
Average	0.79 kW
Minimum	0.30 kW
Maximum	1.56 kW

Average Daily Electricity Consumption



Average	19.0 kWh/Day
Minimum	15.8 kWh/Day
Maximum	21.4 kWh/Day

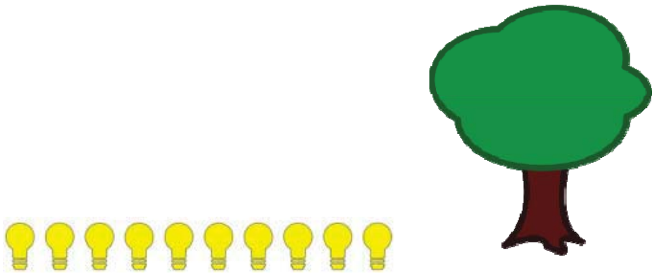
Average Daily Electricity Consumption 2015



Average	15.3 kWh/Day
Minimum	12.7 kWh/Day
Maximum	19.0 kWh/Day

Post-Retrofit Period:
1st Apr 2016-28th Apr 2016

Monthly Electricity Usage (Average Daily) and Trees Equivalent

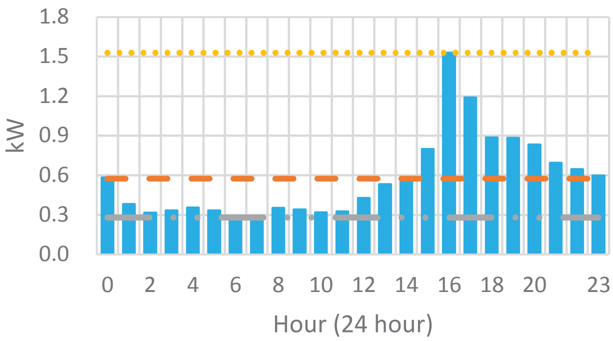


13.8
kWh/Day

28%

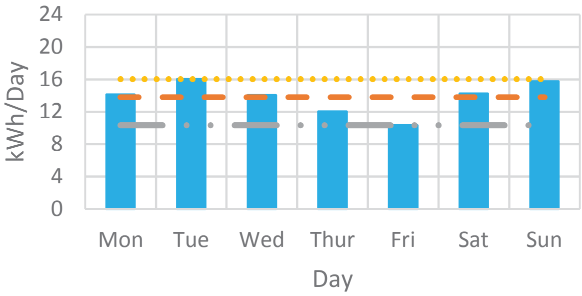
2.2
Trees Equivalent

Average Hourly Electricity Consumption



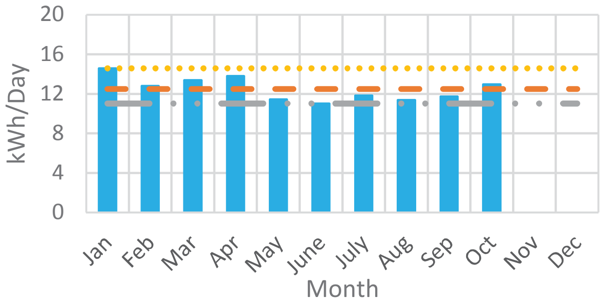
Average	0.57 kW
Minimum	0.28 kW
Maximum	1.53 kW

Average Daily Electricity Consumption



Average	13.8 kWh/Day
Minimum	10.3 kWh/Day
Maximum	16.0 kWh/Day

Average Daily Electricity Consumption 2016



Average	12.5 kWh/Day
Minimum	11.0 kWh/Day
Maximum	14.6 kWh/Day

Appendix G. Energy Consumption Feedback Survey

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HOME HEATING FEEDBACK

Date: ______________________

House No ☐

1) In general, how would you rate the warmth of your house (i.e. your thermal comfort satisfaction with your house)?

Very satisfied	Generally satisfied	Neither satisfied nor dissatisfied	Generally dissatisfied	Very dissatisfied

2) How would you rate the internal temperature and level of comfort in your house during the winter months?

	Much too cold	Too cool	Comfortably cool	Comfortable	Comfortably warm	Too warm	Much too hot
Mornings							
Evenings							

3) Which (if any) of the heating tips did you implement?

	Tick	Comment
Lower thermostat setting		
Check/lower water heating thermostat setting		
Vary TRV settings		
Use extra blankets		
Reduce showering time		
Turn off hot water while shaving/using shampoo etc.		

4) Current settings

Thermostat ☐ WH Thermostat ☐ TRV ☐

5) Did you find the gas usage reports and heating tips useful? Any other comments on heating?

____

____

____

____

HOME ELECTRICITY FEEDBACK

Date: ______________________

☐ **House No**

1) Do you have one of the following in your house? If so, then to what extent are these various household appliances considered as a necessity or a luxury? How long are these powered/used daily?

	Number	**Luxury/necessity**	**How long are these used/powered daily?**
Dishwasher			
Washing machine			
Tumble dryer			
TV			
DVD			
Computer, laptop, tablet			
Games console			
Mobile phone			
Fridge/freezer			
Microwave			
Electric cooker (grill, oven)			
Electric toothbrush			
Electric heater/fire			
Other			

2) On an average weekday (April-October), when are the lights in your house turned on?

Please mark the hours on the scale below

08:00-09:00		09:00-10:00		10:00-11:00		11:00-12:00		12:00-13:00		13:00-14:00	
14:00-15:00		15:00-16:00		16:00-17:00		17:00-18:00		18:00-19:00		19:00-20:00	
20:00-21:00		21:00-22:00		22:00-23:00		23:00-00:00		00:00-01:00		01:00-02:00	
02:00-03:00		03:00-04:00		04:00-05:00		05:00-06:00		06:00-07:00		07:00-08:00	

3) Which (if any) of the electricity tips did you implement?

	Tick	**Comment**
Use the OWL sensor to find out which appliances are using the most electricity		
Install energy-saving bulbs and turn off the lights when leaving a room		
Buy 'A' rating appliances and turn off appliances when not in use		
Only boil the required amount of water and keep lids on pots when cooking		
Wash clothes at a low temperature and wash full loads at a time		
When using the tumble dryer, separate heavy clothes from light clothes		
Make sure the electric heater has a thermostat and is an appropriate size		
Try to reduce your showering time if at all possible		

4) **Did you find the electricity usage reports and tips useful? Any other comments on electricity or appliances?**

____

____

____

____