Bottom-up Modelling of Energy Demand and Technical Energy Savings Potential in the Irish Residential Sector.

Denis Dineen
BAI, MEngSc

National University of Ireland, Cork
School of Engineering
Department of Civil and Environmental Engineering
Environmental Research Institute

Thesis submitted for the degree of Doctor of Philosophy

April 2013

Supervisor: Dr Brian Ó Gallachóir

Head of Department: Prof Alistair Borthwick

Contents

Declaration

I hereby declare that this thesis is my own work and that it has not been submitted for another degree, either at University College Cork or elsewhere. Where other sources of information have been used, they have been acknowledged.

Denis Dineen

____

Date

____

Acknowledgements

I would like to give thanks and appreciation to:

To the Irish Research Council for Science Engineering and Technology, who funded this research.

My supervisor, Dr Brian O'Gallachoir, for his invaluable support, expertise and encouragement throughout.

To the several anonymous referees who spent their time giving genuinely useful feedback on journal and conference papers and to Dr Alexander Summerfield and Dr Dominic O'Sullivan, the reviewers for this thesis, for their valuable comments which contributed greatly to its completion. .

To the staff of Sustainable Energy Authority of Ireland for their help and support and the provision of the data without which this work would not have been in possible, in particular those in the Energy Modelling Group and the Energy Policy Statistical Support Unit.

To the staff at the Environmental Research Institute and the Department of Civil and Environmental Engineering for providing the research facilities and administrative support.

To all my friends and colleagues in the ERI, to all those who contributed to the daily lunchtime conversations and banter, and particularly to my fellow PhD students in the SERG and EPMG for making G24 a great place to work every day.

To the many good friends I made on the hills and crags of Munster during my time in UCC

To my old friends

And in particular, of course, to my family, without whom this wouldn't have been possible!

Executive summary

The International Energy Agency has repeatedly identified increased end-use energy efficiency as the quickest, least costly method of green house gas mitigation, most recently in the 2012 World Energy Outlook, and urges all governing bodies to increase efforts to promote energy efficiency policies and technologies. The residential sector is recognised as a major potential source of cost effective energy efficiency gains. Within the EU this relative importance can be seen from a review of the National Energy Efficiency Action Plans (NEEAP) submitted by member states, which in all cases place a large emphasis on the residential sector. This is particularly true for Ireland whose residential sector has historically had higher energy consumption and CO_2 emissions than the EU average and whose first NEEAP targeted 44% of the energy savings to be achieved in 2020 from this sector.

This thesis develops a bottom-up engineering archetype modelling approach to analyse the Irish residential sector and to estimate the technical energy savings potential of a number of policy measures. First, a model of space and water heating energy demand for new dwellings is built and used to estimate the technical energy savings potential due to the introduction of the 2008 and 2010 changes to part L of the building regulations governing energy efficiency in new dwellings. Next, the author makes use of a valuable new dataset of Building Energy Rating (BER) survey results to first characterise the highly heterogeneous stock of existing dwellings, and then to estimate the technical energy savings potential of an ambitious national retrofit programme targeting up to 1 million residential dwellings. This thesis also presents work carried out by the author as part of a collaboration to produce a bottom-up, multi-sector LEAP model for Ireland.

Overall this work highlights the challenges faced in successfully implementing both sets of policy measures. It points to the wide potential range of final savings possible from particular policy measures and the resulting high degree of uncertainty as to whether particular targets will be met and identifies the key factors on which the success of these policies will depend. It makes recommendations on further modelling work and on the improvements necessary in the data available to researchers and policy makers alike in order to develop increasingly sophisticated residential energy demand models and better inform policy.

Units and Abbreviations

Acronym	Meaning
BE	Better Energy: The National Upgrade Programme
BEH	Better Energy: Homes
BER	Building Energy Rating
BR	Building Regulations
CSO	Central Statistics Office
DCENR	Department of Communications, Energy and Natural Resources
DEAP	Dwelling Energy Assessment Procedure
DoEHLG	Department of the Environment, Heritage and Local Government
EED	Energy Efficiency Directive
EPBD	Energy Performance of Buildings Directive
EPC	Energy performance Certificate
ESB	Electricity Supply Board
ESD	Energy Services Directive
ESRI	Economic and Social Research Institute
GHG	Greenhouse Gas Emissions
GVA	Gross Value Added
GWh	Giga Watt hours
HESS	Home Energy Savings Scheme
HIW	Highly Insulated Wall
IEA	International Energy Agency
IW	Insulated Wall
LEAP	Long Range Energy Alternatives Planning system
MPCDER	Maximum Permitted Carbon Dioxide Emission Rate
Mtoe	Mega Tonnes of Oil Equivalent
NAS	National Administration System Database of BER results
NEEAP	National Energy Efficiency Action Plan
NSAI	National Standards Authority of Ireland
NSHQ	National Survey of Housing Quality 2001/2002
OSeMOSYS	Open Source Energy Modelling System
PISW	Partially Insulated Solid Wall
SEAI	Sustainable Energy Authority of Ireland
TFC	Total Final Consumption
TGDL	Technical Guidance Document to Part L of the Building Regulations
TPER	Total Primary Energy Requirement
UICW	Un-Insulated Cavity Wall
UISW	Un-Insulated Solid Wall
WHS	Warmer Homes Scheme

List of figures

List of tables

Chapter 1

1 Introduction

1.1 Background

Energy consumption in buildings accounted for 41% of total final energy consumption (TFC) in Europe in 2010, making it the largest end-use sector, followed by transport (32%), and industry (25%). The residential sector accounts for 76% of total building floor area [1]. For Ireland the residential sector counted for 25% of TFC in 2011, (32,982GWh or 2,836ktoe) [2]. EU wide the residential sector has been identified as a major potential source of energy efficiency improvements, with the economic energy savings potential estimated at 930TWh or 80Mtoe across member states, or 31% of the total economical energy savings identified [1]. For Ireland in particular there is an incentive to examine closely residential sector energy consumption with a view to increased efficiency, as Ireland has historically had high energy demand and associated green house gas emissions from this sector. In 2006, the climate corrected energy usage per dwelling in Ireland was 27% greater than for the UK, 31% higher than the EU15 average and 36% higher than the EU27 average. Similarly in 2006 climate corrected electricity demand was 20%, 17% and 29% than the UK, EU15 and EU27 respectively. There are a number of historical reasons for this. The EU ODYSSEE project notes that it is member states that have moderate climates, such as Ireland, that typically have the highest space heating energy requirements. Such countries would historically have had less impetus to invest in energy efficient dwelling construction technologies than those with harsher winters, yet still required considerably longer heating seasons than those in Mediterranean climes.

1.1.1 Overview of the Irish dwelling stock

Data on the make-up of the residential dwelling stock in Ireland is primarily taken from the Central Statistics Office (CSO) national census, the most recent of which was undertaken in 2011 [3]. The next section briefly sets out some of the key data available so as to give the reader an overview of the current state of the Irish residential stock and to highlight some key features of the Irish stock which may differ from the norm in other EU countries.

1.1.1.1 Number and age profile of dwellings

The number of occupied dwellings in Ireland has been increasing steadily since the middle of the last century, at which time Irelands population had reduced to a historical low point of 2.8 million people. The numbers of people and permanently occupied dwellings are given in Table 1.1. Since then the population has grown by 63% to 4.59 million while the average number of persons per dwelling has fallen from 4.2 to 2.8, resulting in an increase in the number of permanently occupied dwellings of 144% to reach 1.65 million in 2011. The more recent history of Irelands dwelling stock is dominated by the housing market and construction boom experienced in the period 2002-2007, resulting in the massive spike in numbers of new dwellings completed annually as shown in Figure 1.1. One result of this is that 26% of dwellings occupied in 2011 had been constructed after 2001, giving Ireland one of the youngest housing stocks in Europe. The period of construction of dwellings recorded in the 2011 census is given in Figure 1.2. Another result of the speculative nature of much of the construction at the height of the boom is the peculiar phenomenon of large numbers of unoccupied, or vacant dwellings, estimated at 230,000 in the 2011 census. Discussing these trends and comparing the situation in Ireland to other European countries the 2009 European Housing Review notes the following [4]:

"*There is a long history of poor housing conditions. In 1980, the country had the lowest number of dwellings per thousand inhabitants in the old EU. It still has worse housing conditions than other countries with similar living standards, despite the recent building boom, with floor areas per person of around a fifth less than the western European average. Household size is also relatively high at 2.94 persons in 2002, though it had improved from 3.34 in 1991. Undoubtedly, the historic lack of dwellings was a root cause of the recent long housing boom.*"

Year	1961	1971	1981	1991	1996	2002	2006	2011
Population	2,818,341	2,978,248	3,443,405	3,525,719	3,626,087	3,917,203	4,239,848	4,588,252
Number of permanently occupied dwellings	676,402	726,332	896,054	1,019,723	1,114,974	1,279,617	1,462,296	1,649,408
Persons/dwelling	4.2	4.1	3.8	3.5	3.3	3.1	2.9	2.8

Table 1.1: *Population and dwelling numbers for Ireland, 1961 - 2011*

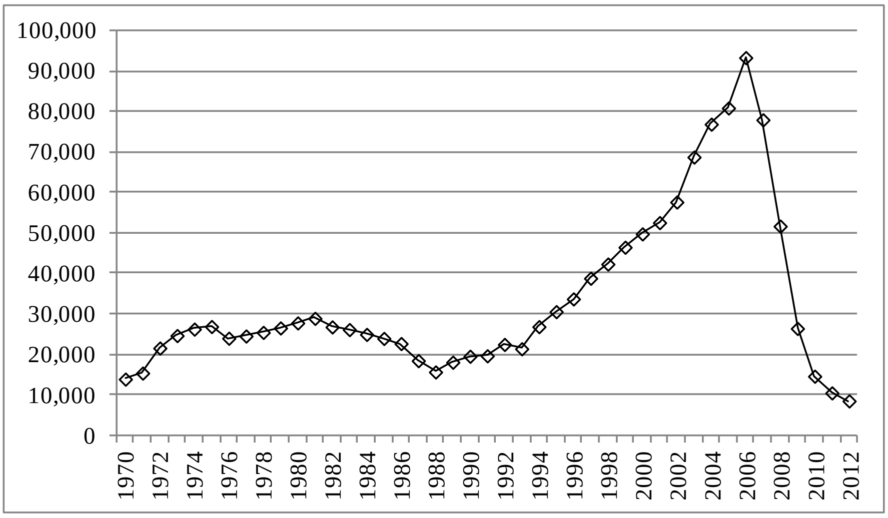

Figure 1.1: *Number of dwellings constructed per annum*

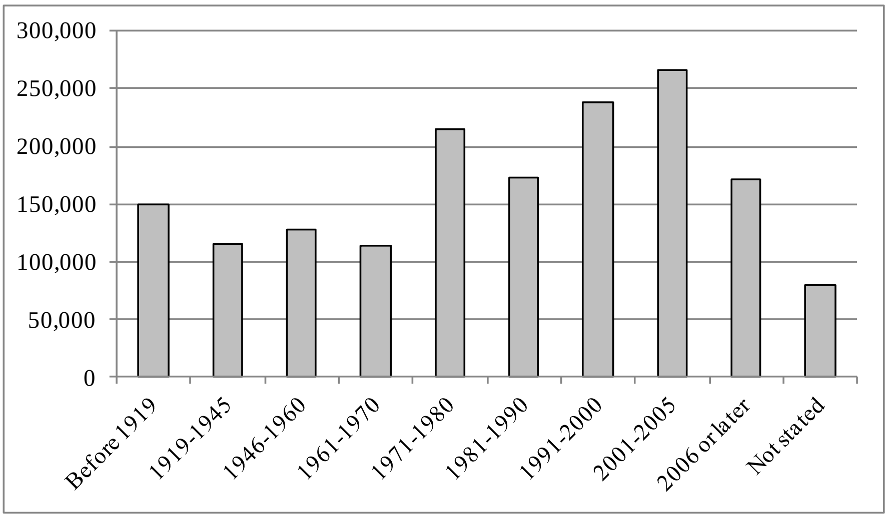

Figure 1.2: *Age profile of dwellings in 2011*

1.1.1.2 Dwelling floor areas

As well as the large increases in the number of dwelling in the Irish dwelling stock the floor areas of dwellings newly constructed has risen significantly in the period since 2002 with the average floor area of all houses (excluding apartments) increasing by 44% in the period from 144m^2 to 207m^2 in 2012, as shown in Table 1.2 and Figure 1.3. Appendix F contains further data on floor area including a table reproduced from the Housing Statistics in the European Union 2010 report which compares what data is available on floor areas across the EU[5]. This indicates that average floor areas per dwelling in Ireland are at the upper end of the spectrum observed across the EU (though not floor areas per person, due to the above average occupancy rate).

Floor area m²	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Houses	149	144	148	148	149	159	164	168	176	192	190	207
Multi development houses	131	120	119	119	125	128	133	133	133	136	135	142
One off houses	186	192	199	205	214	224	238	248	253	250	249	248
Apartments	78	78	80	77	78	81	85	85	93	91	103	90

Table 1.2: *Average floor area of dwellings applying for planning permission*

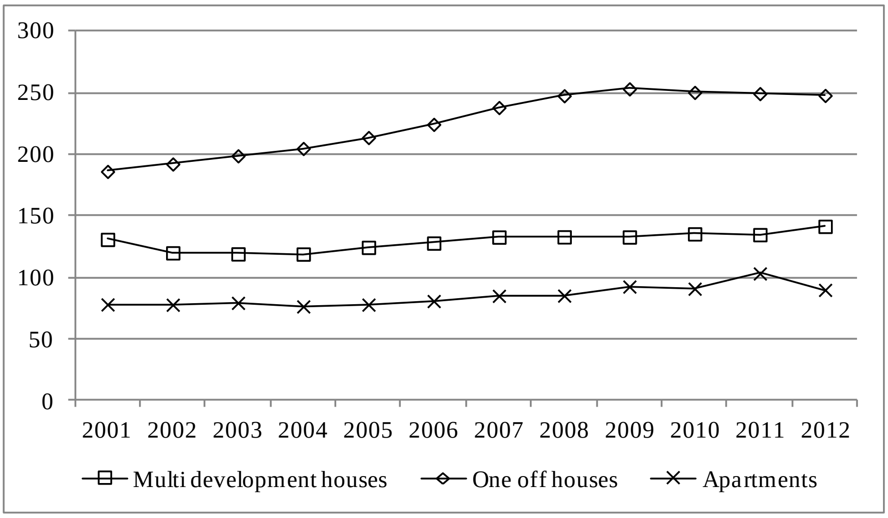

Figure 1.3: *Average floor area of dwellings applying for planning permission*

1.1.1.3 Building types and fuel types

Data from the 2011 census on split between different building types and central heating fuel types present in the residential dwellings stock is given in Table 1.3. With regard to building type it can be seen that one off detached houses form the largest share accounting for 43% of the total dwelling stock, with apartments making up the smallest share with 12%. With regard to central heating system fuel type oil fired boilers form the largest share with 44% of all dwellings, with gas making up a further 34%. Figure 1.4 shows separately the numbers of dwellings split by building type and central heating fuel type for dwellings in rural and urban areas. As might be expected, rural areas consist of a greater proportion of detached dwellings while urban areas contain greater numbers of semi-detached and terraced dwellings along with the vast majority of apartments. With regard to fuel types, the key underlying factor is the presence of the national gas grid in urban areas but not in rural, which has lead to oil becoming the central heating fuel type of choice for rural Ireland. Referring to Table 1.3 detached houses with oil fired central heating account for 460,525 out of a total of 1,624,098 dwellings or 28% of all dwellings. The significance of oil as a heating fuel is increased by the fact that, referring to Figure 1.3, the detached houses where it predominates have significantly greater floor areas than the semi detached houses gas fired dwellings or electrically heated apartments.

Number of dwellings:		Oil	Natural Gas	Solid Fuels	Electricity	All Other
Aggregate Rural Area	Detached House	353,298	6,302	103,931	10,284	21,611
	Semi-detached House	40,200	3,714	14,790	2,403	2,401
	Terraced House	12,900	1,894	5,974	1,777	1,405
	Apartment	3,264	1,011	872	3,375	641
Aggregate Town Area	Detached House	107,227	75,413	10,269	6,517	5,017
	Semi-detached House	131,355	222,535	19,623	12,619	7,011
	Terraced House	51,649	159,559	19,945	18,145	8,577
	Apartment	7,114	74,739	1,680	83,111	7,475

Table 1.3: *2011 residential dwelling stock split by building type and central heating fuel type*

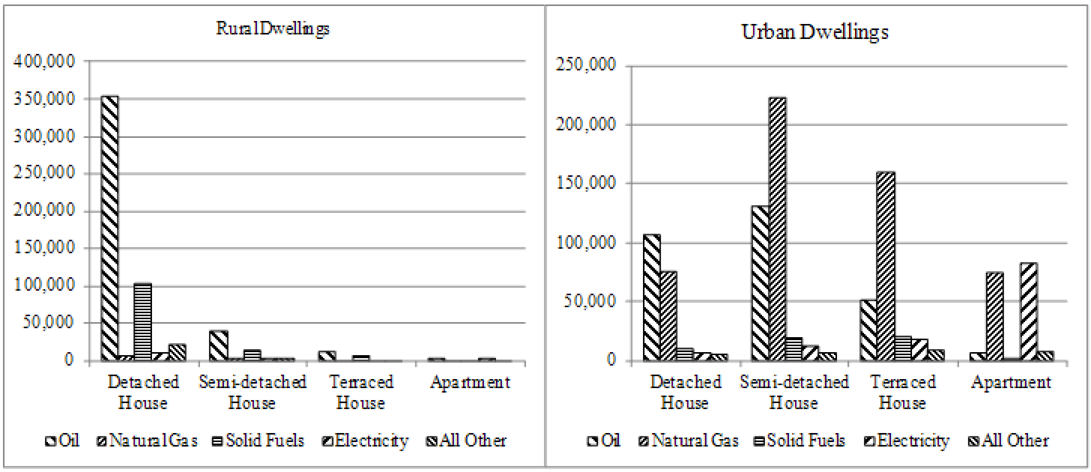

Figure 1.4: *2011 Residential dwelling stock split by building type and fuel type*

1.1.2 Irish residential sector energy policy.

Current Irish national residential sector energy policy is framed by the EU Energy Efficiency Directive (EED), which has recently superseded the Energy Services Directive (ESD) and the recast Energy Performance in Buildings Directive (EPBD). Under the first National Energy Efficiency Action Plan (NEEAP) the residential sector has been targeted for the greatest share of energy savings, accounting for 44%, or 10,355 GWh of the savings from identified measures in the first NEEAP, with a further 5,200 GWh of savings targeted from a national residential retrofit programme announced subsequently. The national residential retrofit programme is a recognition of both the scope for and the need to implement cost effective energy efficiency measures in the sector. The retrofit programme has been launched as the Better Energy: Homes (BEH) scheme and aims to retrofit almost 1 million residential dwellings, out of a total stock of 1.6 million. As such it is one of the most ambitious and far reaching energy related projects ever proposed by the state. The report by the National Economic and Social Council secretariat concludes that it is "*by far the most important policy intervention available to Ireland to reduce emissions in the period to 2020*" [6]. As well as its contribution to meeting energy efficiency targets the scheme is also a core plank of the government's job creation strategy for the construction sector, which has been particularly badly hit by the economic recession and the bust in the property market.

The energy efficiency requirements for newly constructed dwellings are set out in part L of the building regulations, dealing with the conservation of fuel and energy in dwellings. In Ireland the first building regulations to specify minimum insulation and thermal energy efficiency requirements were introduced in 1979, and dwellings constructed prior to this, unless subsequently altered, would have relatively poor energy efficiency characteristics. A series of subsequent reviews to part L of the building regulations in 1992, '97 and '02 meant that a dwelling built in 2003 theoretically had a 76% reduced heating demand relative to the equivalent dwelling built in 1979. Further improvements to the regulations in 2008 and 2010 aimed to achieve technical energy savings of 40% and 60% respectively, relative to the 2002 regulations. This theoretical technical energy efficiency improvement has been offset by parallel trends of growing numbers of dwellings, increasing floor area per dwelling and the spread of central heating systems leading to greater comfort levels [7].

Energy modelling in Ireland is carried out at a national level by the Sustainable Energy Authority of Ireland (SEAI). SEAI produce a number of annual reports on various national energy statistics and indicators, as well as future energy forecasts. The last report to deal specifically in detail with the residential sector was published in 2008[7]. Currently the energy forecast reports focus on the period to 2020 and are generated largely using top-down econometric modelling to produce a baseline or reference energy demand projection which is then adjusted to account for the impact of individual policy measures using bottom-up calculations. The 2009 energy forecasting report identified possible limitations of this approach and called for improved bottom up modelling on a disaggregated sectoral level [8].

1.2 Aims

The principle objective of this thesis was to use a bottom-up modelling approach to examine the energy demand characteristics of the Irish residential sector and to model the potential effects of the main government policy measures in this area. Following from this two key research questions were asked:

- What is the energy savings potential in 2020 due to the introduction of the 2008 and 2010 revisions to the building regulations governing the conservation of fuel and energy in dwellings?
- What is the energy savings potential of an ambitious scheme aiming to carry out energy efficiency retrofit works on up to 1 million existing dwellings?

1.3 Methodology

A detailed description of the methodology used to address each of the above research questions is provided in the subsequent chapters. Presented here is an overview of the main approaches to modelling residential sector energy demand as well as an acknowledgement of the inherent weaknesses of such models.

1.3.1 Overview of possible approaches

Energy demand modelling has been classified *inter alia* by Weyant and Hill (1999) [9], Canes (2002) [10] and Huntington and Weyant (2004) [11]. A review of the various different types of energy models employed specifically in the residential sector has been carried by Swan & Ugursal [12]. One major division typically identified is between so-called ‘top down’ models which are typically based on macroeconomic social accounting matrices, and ‘bottom up’ models which can describe in greater detail the expected impact of changes in technology or input costs within particular product markets. Despite the distinction being widespread, the two categories of bottom-up and top-down aren’t mutually exclusive, there also exists a “hybrid” class where the two approaches are combined; one of the main contributions of the hybrid approach is the detection of missing information and dynamics that simple top-down or bottom-up models cannot detect on their own [13]. The distinction is still useful however to highlight in broad terms the differences between the two types of approach.

Top-down models use macro level data on the residential sector, population and economy as a whole as inputs. Typical top-down data requirements may include historical energy demand, GDP, disposable income, energy prices, population, number of households, number of appliances etc. By their nature they are ideal for market based analysis of energy consumption trends, for analysing the long term effects of fuel and technology costs and the effectiveness of market based policy initiatives such as tax breaks and financial incentives, which can be modelled as reduced costs. Using econometrics based on historical data and trends as a basis for estimating future consumption has the advantage that the model may be calibrated to give results consistent with past experience. Some disadvantages of this approach include that it is less able to deal with future scenarios that exhibit fundamental changes relative to past experience and top-down market based models typically cannot explicitly model the impacts of purely technical measures and improvements.

In contrast, bottom-up models use micro level data as inputs, focusing on the energy demand of individual dwellings or of energy end-uses within a dwelling, which are then aggregated and extrapolated to the regional or national scale. Typical bottom-up data inputs include the energy consumption of individual household appliances, insulation thicknesses, boiler characteristics etc. Bottom-up models therefore have a high input data intensity. The strength of the bottom up approach is its potential to model the effects of new energy technologies, which may produce step changes to patterns of energy consumption and for which general historical trends cannot be used as an indication of future performance. Disadvantages of a bottom-up technology focused modelling approach include the fact that the large amounts of low level data can be difficult to obtain, in many cases because it has never been historically collected in an organised manner, or in other cases because the necessary data is private, such as individualised household energy bills. Another disadvantage is that if such models are not directly calibrated against actual energy consumption data, inaccuracies in any one of a large array of input variables may lead to significant errors in the estimation of final energy demand. Sources of such errors may include assessor errors during on-site inspection or during input of data into model, poor workmanship or non compliance with regulations during dwelling construction resulting in building elements having less than the assumed level of performance etc. A further disadvantage is that it is less able to account for changes in occupant behaviour and energy use not linked to purely technology considerations such as fuel prices, fuel poverty, occupancy patterns, rising expectations of comfort in homes, increased awareness of the need for energy conservation etc. These non technical factors can lead to physically identical dwellings consuming significantly different amounts of energy. This limitation is well recognised and documented [14-18].

In response to the limitations inherent in pure top-down and bottom-up approaches there have been calls for a shift toward integrated hybrid modelling systems that include multidisciplinary and dynamic approaches [17, 19]. Hybrid models seek to combine the strengths of both the top-down and bottom-up approaches and can also potentially incorporate elements from the social and behavioural sciences. An advantage of a hybrid approach is that it can overcome the weaknesses specific to either of the traditional one-sided approaches. Key to such an integrated approach is the collaboration and cooperation of experts across the range of disciplines involved, including economists, sociologists, psychologists, engineers, statisticians etc.

1.3.2 Rebound effect

Reviews of the literature available on rebound effects have been carried out, amongst others, by Greening et al [20], Sorrel et al [21] and Chitnis et al [22], with the latter two in particular focusing on rebound from residential sector energy efficiency measures. Both Greening and Sorrel point to difficulties caused by the lack of a standard set of definitions, with Sorrel noting that "*interpretation of the evidence is greatly hampered by the use of competing definitions, measures, terminology and notation"*; however a concise description is provided by Chitnis et al [22]: "'*Rebound effects' is an umbrella term for a variety of behavioural responses to improved energy efficiency. The net result of these effects is typically to increase energy consumption and carbon/GHG emissions relative to a counter factual baseline in which these responses do not occur. As a result, the energy and emissions saved by the energy efficiency improvement may be less than anticipated*". Chitnis further offers a classification system for different forms of rebound effects that introduces five distinctions highlighting important differences between: direct versus indirect rebound, energy versus emissions rebound, efficiency versus sufficiency rebound, direct versus embodied energy use and income versus substitution rebound effects.

To give relevant some examples, direct rebound effect would describe the phenomenon whereby the level of roof or wall insulation in a dwelling is improved increasing the space heating energy efficiency. The occupants may choose to maintain the same levels of thermal comfort after retrofit as existed before, in which case all of the efficiency gains are realised as reductions in energy consumption and expenditure. This is not typically the case however, and usually the occupants will choose to realise some or potentially all of the efficiency gains in the form of increased comfort, through some combination of increased internal temperatures, increased heating hours or increased proportion of the floor area being heated. This then causes the actual realised savings to be less than the theoretical maximum savings achievable had there been no increase in comfort levels, and a model that fails to take into account some likely degree of increased thermal comfort post retrofit will overestimate the savings achieved by the measure. It is difficult to estimate the likely scale of this direct rebound as it is highly dwelling and occupant specific and requires detailed data on the level of thermal comfort experienced prior to retrofit works being carried out and the financial situation of the occupants, specifically whether they are experiencing fuel poverty, i.e. an inability to heat their homes to desired levels due to financial constraints. This data is not commonly available.

In contrast the indirect rebound effect describes the phenomenon whereby following improvement to the dwellings space heating energy efficiency, the energy consumption of the dwelling decreases and so too does the household expenditure on fuel. The occupants may choose to spend the savings generated on goods and services that they would not otherwise be able to afford, and these good and services will themselves have associated energy demand and green house gas emissions, which may be accounted as off-setting the reductions in energy and green house gas emissions achieved through the space heating energy efficiency improvement measure in the first place. The example of indirect rebound serves to illustrate to width of potential effects that may or may not be included in a definition of rebound effect. Greening notes that “*Depending on the definition used for the rebound, the size of this effect can be either insignificant or can result in an increase in fuel consumption*”.

Both of the above examples illustrate the fact that rebound effects are strongly linked to economics, and reinforce the point raised in the discussion in section 1.3.1 that a bottom-up technology focused model which fails to incorporate the economics of household expenditure on energy consumption will have inherent difficulties in endogenously accounting for any form of rebound effects.

1.3.3 Approach adopted for this thesis

Referring to section 1.2, given the aim of estimating the energy savings potential of two specific policy measures which have a strong technical focus, namely building regulations affecting newly constructed dwellings and a national retrofit scheme affecting the technical energy efficiency of the existing dwelling stock, the author choose a bottom-up engineering archetype approach. Swan and Ugursal [12] describe the characteristic approach of the archetype method as follows: "*This technique is used to broadly classify the housing stock according to vintage, size, house type, etcetera. It is possible to develop archetype definitions for each major class of house and utilize these descriptions as the input data for energy modeling. The energy consumption estimates of modeled archetypes are scaled up to be representative of the regional or national housing stock by multiplying the results by the number of houses which fit the description of each archetype*." The appropriateness of the bottom up engineering approach for modelling measures with such a technical focus is again highlighted by Swan and Ugursal: *"If the objective is to evaluate the impact of new technologies, the only option is to use bottom-up* [engineering method] *techniques. This is a point of emphasis because compared to taxation and pricing policies, technological solutions are more likely to gain public acceptance to reduce energy consumption and associated greenhouse gas emissions".* The author has not attempted to incorporate hybrid cross-disciplinary elements into the modelling methodology to account for behavioural effects, focusing instead on creating a comprehensive engineering archetype model that estimates the technical energy savings potential within the residential sector. The author fully acknowledges the importance of occupant behaviour in predicting real world outcomes, and considers that this work presents an upper bound on the energy savings potential under each of the scenarios considered. The value of this approach is again recognised by Natarajan et al [17] who, while rightly pointing to the limitations of the bottom-up models in their inability to endogenously account for occupant behaviour, also note that "*they are very useful in identifying a baseline technical potential for future emission reductions*".

1.3.4 Interpreting model results in light of assumptions and uncertainties

The discussion in section 1.3.2 on rebound effects and the degree to which they can affect potential energy savings, depending amongst other factors on the definitions and assumptions used, illustrates the point that for all models it is necessary to appreciate the underlying assumptions and methodologies employed to successfully interpret the model results. A given set of model results should generally not be taken at face value but always placed in the context of the many technical and non technical assumptions underpinning the analysis and the associated caveats. All modelling of real world problems requires them to first be simplified, and all assumptions are inaccurate to some degree. The adage "*all models are wrong ; the practical question is how wrong do they have to be to not be useful*" applies [23]. Useful conclusions for policy makers can be drawn from models even if they do not account for the full complexity of real world effects and counter effects. For policy makers the crucial issues should not be to know exactly how many kWh savings will be achieved at a particular point in the future, but rather to what policy options are robust in the face of a range of potential future scenarios and the many uncertainties involved.

1.4 Thesis in brief

1.4.1 Overview

The author began by developing a bottom-up model of the space and water heating energy demand of newly occupied dwellings from 2007 to 2020. This model is used to estimate the energy savings potential of the 2008 and 2010 building regulations governing the conservation of fuel and energy in dwellings. The author notes that the significant improvements to the building regulations governing fuel efficiency in 2008 and 2010 come just after the end of the largest construction boom in the state's history and at a time where the construction of new dwellings is highly depressed. The author asks what the effect would have been had the regulations been introduced in 2002 so as to apply to dwellings built during the boom. This lead to the publication of a journal paper titled "Modelling the impacts of building regulations and a property bubble on residential space and water heating", which forms the basis for Chapter 2 of this thesis. At this stage, having created a bottom up model of the energy demand of space and water heating in new dwellings, in order to begin to expand this to a general model of all residential sector energy demand, the author made an initial top-down estimate of the energy consumption of the other two main sources of energy demand in the residential sector: space and water heating in existing dwellings and lighting & electrical appliances. Both of these were identified as areas for further work.

In order to bring together the three separate strands of work described above into a single residential sector model the LEAP software package was used. This residential sector LEAP model then formed part of the Ireland LEAP model, which also included bottom up models of the transport, industry and services sectors developed by the Energy Policy and Modelling Group in UCC. This model contributed to the 2010 SEAI energy forecasting report [24] and was the basis for the following peer reviewed journal paper [25]. As part of the residential LEAP model work was carried out on bottom up modelling of both the space and water heating of existing dwellings and lighting & appliances. For lighting & appliances the author used detailed data from SEAI and ODYSSEE on the percentage penetration rates and specific energy consumption of a number of end uses to estimate the growth in energy demand. The author concluded from this initial work that more detailed modelling in this area would benefit from adopting a hybrid approach to account for the significant influence of behaviour and usage patterns on this end-use. It was decided that this was outside the scope of this thesis, and is left for further work. Also as part of the Ireland LEAP project an initial bottom up model of the space and water heating energy demand of existing dwellings was developed, based on energy performance ratings. Retrofit improvements were simulated as an upward shift in energy performance bands, based on some simplified assumptions. Further development of this model was chosen as the next strand of work to focus on. As the work carried out as part of the Ireland LEAP project was a collaboration it is included as Chapter 5 of the thesis, and draws on material from the paper currently in review, of which I am a co-author, looking at the overall Ireland LEAP model, along with a more detailed description of the residential portion of the model of which I am the lead author. A fuller description of the author’s role in the collaboration is given in section 1.6.

The simple model of retrofit measures carried out on existing dwellings that had been developed for the LEAP model was then used as a starting point for more a detailed analysis. The simple assumptions regarding the improvement profile of dwellings becoming retrofitted was developed into a more sophisticated matrix of likely improvement levels based on bottom up modelling of the effects of individual retrofit measures on sample dwellings. This work lead to a conference papers presented to the International Energy Workshop 2011 and to the National Economic and Social Council secretariat. Despite the significant improvements made to the model at this point, the modelling approach adopted thus far of simulating retrofit as an improvement in energy performance ratings had some particular draw backs as it did not allow detailed bottom up modelling of the effects of individual retrofit measures nor did it allow any estimation of the potential scale of rebound effects, and did not take sufficient account of the fact that certain retrofit measures can only be implemented in dwellings with particular wall construction types. Furthermore the LEAP software was found not to be ideally suited for directly constructing highly disaggregated bottom up models containing large numbers of archetypes. These factors, along with the availability of improved data, lead us to develop an improved model of residential retrofit energy savings potential using wall construction type as a key variable. This work resulted in a methodological paper which forms the basis of chapter 3, and a paper on the development of a number of detailed scenarios exploring the range of potential energy savings from the introduction of the national residential retrofit programme, which form the basis of chapter 4.

1.4.2 Chapter Summaries

Chapter 2: A bottom up model of space and water heating in new dwellings from 2007 to 2020 is developed. This is used to estimate the potential energy savings due to the introduction of the 2008 and 2010 building regulations governing the conservation of fuel and energy in dwellings. The author also examines the affect that the construction boom experienced in Ireland from 2002 to 2006 will have on the effectiveness of these regulations. This chapter is based on the following peer reviewed journal paper:

- **D. Dineen**, B.P. Ó Gallachóir, Modelling the impacts of building regulations and a property bubble on residential space and water heating, Energy Buildings (2010), doi:10.1016/j.enbuild.2010.09.004.

Chapter 3: A methodology is developed to model the space and water heating energy demand of existing dwellings using data collected through the EU Energy Performance Certificate(EPC) scheme, using Ireland as a case study. The model uses 175 archetype dwellings that focus on three key dwelling characteristics, namely building type, energy performance and notably, wall construction type. The modelling methodology allows the estimation of the energy savings that can be achieved for a range of retrofit measures across all dwelling types. The potential scale of direct rebound effects is also estimated. Earlier stages of the work developed in this chapter were presented as the following conference papers:

- **Dineen D**., Rogan F. and Ó Gallachóir B. P., 2010 Bottom up modelling of energy savings due to the National Retrofit Programme for Ireland's Housing Stock Proceedings 9th YEEES (Young Energy Economists and Engineers Seminar) November 26 - 27 2010 Trinity College Dublin.
- **Dineen D**., Rogan F., Cronin W. and Ó Gallachóir B. P., 2011 Modelling residential energy savings due to Ireland's National Retrofit Programme using DEAP and LEAP. Proc International Energy Workshop 2011 Stanford University July 6 -9 2011, Stanford CA.

Chapter 4: The technical energy savings potential of an ambitious national retrofit programme of measures targeting energy efficiency of the space and water heating end uses of the 2011 stock of residential dwellings between 2012 and 2020 is estimated. This estimate is carried out using the bottom up model of the space and water heating energy consumption described in the previous chapter. The analysis and conclusions of this chapter formed the basis of

- **Dineen D**., Chiodi A. and Ó Gallachóir B. P 2012 Residential Sector – Technologies and Policies. Proc. UCD NESC Workshop on GHG Reductions 17th May 2012

Chapter 5: This chapter presents the work carried out by the University College Cork Energy Policy & Modelling Group as part of the Ireland LEAP project. It gives an initial overview of the entire project and the broad approach taken for modelling individual subsectors of the economy, and then focuses on the modelling methodology adopted for the residential sector. Results are shown for both the overall model and in more detail for the residential sector. This chapter is based on the following peer reviewed journal paper:

- Rogan F., Cahill C., Daly H.E., **Dineen D**., Deane J.P., Heaps C., Welsch M., Howells M., Bazilian M., Ó Gallachóir B.P. 2013 LEAPs and Bounds - An Energy Demand and Constraint Optimized Model of the Irish Energy System. Energy Efficiency (In Press)

This work also formed the basis of a chapter in the following report:

- Daly, H., **Dineen, D**., Rogan, F., Cahill, C., Bottom-Up Energy Demand Modelling - LEAP Ireland, Section 7 of Clancy M., Scheer J. and Ó Gallachóir B. P., 2010, Energy Forecasts in Ireland to 2020; 2010 Report. 2010, Sustainable Energy Authority of Ireland.

1.5 Data availability

At the outset of this thesis data on energy consumption in the Irish residential sector was available at an aggregate level for the sector as a whole but disaggregated data at the level of individual end uses was lacking. Data on overall fuel use in the residential sector was available from the national energy balance and estimates of the floor area of newly built dwellings were available based on planning applications. While some provisional estimates on end use energy consumption had been made by SEAI for the 2008 energy in the residential sector report [3], data at this level of detail was generally unavailable. Some data on household energy expenditure was available but this could not readily be linked to dwelling energy demand. Over the course of the thesis more detailed data became available and allowed for improvements and changes to the modelling approaches adopted. The first significant improvement came about through the involvement of the Energy Policy and Modelling Group with SEAI on the LEAP project. As part of this project SEAI made available a snap shot of the NAS BER database containing approximately 100,000 dwellings which allowed the characterization of the stock of existing dwellings by BER band for work carried out as part of the LEAP project. At a later stage an expanded, more detailed version of the NAS data was made available publicly online and this again facilitated more detailed analysis than was previously possible. Significant gaps in the available data remain, in particular there is a lack of data linking actual metered energy consumption to detailed descriptions of physical characteristics of dwellings.

1.6 Role in collaborations

Chapters 2, 3 and 4 of this thesis are based purely on my own work and have been submitted as peer review journal papers of which I am the lead author. In all three cases valuable feedback was received from anonymous reviewers as well as my supervisor, Dr Brian O'Gallachoir and in the case of chapter 3 also from my colleague Dr Fionn Rogan. Chapter 5 draws on a collaborative work by members of the Energy Policy and Modelling Group at UCC. This work has been submitted as a peer review journal paper by Rogan, who is the lead author, while I am a co-author on the paper. The modelling work of the residential sector was carried out solely by the author, except for the work presented in section 5.3.2.1, which was carried out in collaboration with Rogan. The following sections, dealing largely with the overall Ireland LEAP model, are based on material originally authored by Rogan and which was re-formatted and edited by the author for inclusion in this thesis: Section 5.2, section 5.4.1, section 5.5.1, section 5.6. The following sections, dealing largely with the residential portion of the LEAP model, were written by the author: Section 5.1, section 5.3, section 5.4.2, section5.5.2, section 5.5.3.

CHAPTER 2

2 Modelling the Impacts of Building Regulations and a Property Bubble on Residential Space and Water Heating.

Abstract

This paper develops a bottom-up model of space and water heating energy demand for new build dwellings in the Irish residential sector. This is used to assess the impacts of measures proposed in Ireland's National Energy Efficiency Action Plan (NEEAP). The impact of the housing construction boom, which resulted in 23% of occupied dwellings in 2008 having been built since 2002, and the subsequent bust, are also assessed. The model structure treats separately new dwellings added to the stock after 2007 and pre-existing occupied dwellings. The former is modelled as a set of archetype dwellings with energy end use affected by the relevant set of building regulations that apply during construction. Energy demand of existing dwellings is predicted by a simpler top down method based on historical energy use trends. The baseline scenario suggests residential energy demand will grow by 19% from 37,285 GWh (3,206 ktoe) in 2007 to 44,310 GWh (3,810 ktoe) in 2020. The results indicate that 2008 and 2010[1] building regulations will lead to energy savings of 3,547 GWh (8.0%) in 2020. Had the 2008 building regulations been introduced in 2002, at the start of the boom, there would be additional savings of 2,768 (6.7%) in 2020.

Keywords: Energy Demand Model; Residential Sector; Bottom Up; Archetype.

[1] At the time of the writing of this paper, which was published in 2010, what we refer to here as the 2010 building regulations were planned for introduction in 2010. It transpired that these regulations were not introduced until 2011 and so came into being as the 2011 building regulations. For this chapter the author reproduces this work in its published format and so continue to refer to them as the 2010 regulations.

2.1 Introduction

The residential sector accounts for a significant portion of energy demand and offers significant opportunity for improved energy efficiency. Within the EU-27, the residential sector accounted for 26% of energy demand [26]. The European Action Plan on Energy Efficiency[27] identifies residential and commercial buildings as having the largest efficiency savings potential (1,791TWh / 154Mtoe) followed by the transport sector (1,221TWh / 105Mtoe) and manufacturing industry (1,105 TWh / 95Mtoe). EU Directive 2003/32/EC (the Energy Services Directive) [28] requires Member States to plan for a cumulative energy savings target of 9% for the non-emissions trading sectors. Member States have each completed a NEEAP in order to comply with this Directive. The residential sector is typically the largest source of savings within NEEAPs accounting for approximately 30% – 50% of the total.

This paper develops a bottom-up model of energy demand in the residential sector for one EU Member State, Ireland, and uses it to assess the impacts of energy savings due to measures proposed in the NEEAP. Although Ireland is chosen here as a case study, the approach is readily replicable for other member states. Ireland has experienced a 51% growth in energy-related carbon emissions from 1990 to 2007 and thus represents an interesting case study, having particular challenges to face in reversing this trend to satisfy its absolute emissions reduction targets for 2020. In Ireland's NEEAP the proportion of overall savings demanded from the residential sector is among the highest of any Member State. In order to meet this challenge, the need for improved modelling in the Irish residential sector has been identified by [29, 30].

The layout of the paper is as follows: Section 2.2 provides the context for modelling the impacts of energy efficiency measures on future residential sector energy demand. Section 2.3 describes the overall methodology and approach used in this paper. Section 0 details the development of the archetype model of space and water heating in new dwellings and Section 2.5 describes the additional work external to the archetype model necessary to consider the energy demand of the residential sector as a whole. Section 2.6 presents the results obtained and analysis carried out in various scenarios while Section 2.7 draws conclusions and discusses the limitations of the approach taken, pointing to further research areas and work to be done.

2.2 Context

Ireland's energy policy priorities are framed in the context of the EU Energy Services Directive (ESD), which requires member states to "..adopt and aim to achieve an overall national indicative energy savings target of 9% for the ninth year of application of this directive, to be reached by way of energy services and other energy efficiency improvement measures..." [31]. The 9% savings are quantified relative to average annual energy use in the period 2001-2005. It also requires countries to set an intermediate target for the year 2010.

All member states were required to submit a first NEEAP in response to the ESD by June 2007, to be followed by a second in June 2011 and a third in 2014. The NEEAPs should detail the improvement measures planned to reach the target and the second and third NEEAPs should include analysis and evaluation of the preceding ones, as well as updated plans and details of new measures to address any existing or projected shortfalls [32]. Ireland submitted its first NEEAP in accordance with the requirements of the ESD. A draft of this was issued for consultation in September 2007 and the final document was released in May 2009. The NEEAP document specifies the measures planned to meet the energy savings target of 9% by 2016 and 20% by 2020 [33]. The inclusion of the 2020 target forms part of national policy as the ESD only requires the NEEAP to specify measures to 2016.

2.2.1 Importance of energy savings from residential sector

The relative importance of the residential sector in achieving the energy efficiency savings targets of member states can be seen from a review of their National Energy Efficiency Action Plans. According to the NEEAPs submitted in 2007 [34], Ireland has targeted the residential sector as the source of the largest share of its energy savings, at 56% of the total in 2016. The UK has similarly targeted the residential sector for 52% of its total savings, Germany 36%, Italy 45% and Czech Republic 31%. In all cases the residential sector was the largest single source of savings identified.

Table 2.1 gives the breakdown of the energy savings measures within the Irish residential sector. The measures can broadly be broken down into two subsets, measures applying to newly built dwellings and measures applying to the retrofitting existing dwellings. The former includes the 2002, 2008, 2010 building regulations and the low carbon homes scheme 2013. It is expected in NEEAP that savings from these four measures will account for 41% and 48% of the total residential savings in 2016 and 2020 respectively[1]. Note that these figures are from Ireland's 2009 NEEAP and take into account the reduced numbers of new dwellings being constructed due to the severe contraction in household construction [35].

Residential Sector	GWhrs in 2016	% in 2016	GWhrs in 2020	% in 2020
Building Regs 2002	1015	13%	1015	10%
Building Regs 2008	1425	19%	2490	24%
Building Regs 2010	570	7%	1100	11%
Low Carbon Homes 2013	130	2%	395	4%
House of Tomorrow Programme	30	0%	30	0%
Warmer Homes Scheme	155	2%	170	2%
Home Energy Saving Scheme	600	8%	600	6%
Smart Meters	650	9%	690	7%
Greener Homes Scheme	265	3%	265	3%
Eco-design for energy using appliances	1200	16%	1200	12%
Efficient Bolier Standard	1600	21%	2400	23%
Total	7640		10355	

Table 2.1: *Breakdown of savings by measure within residential sector as per Ireland's NEEAP 2009*

2.2.2 NEEAP estimation of potential residential sector energy savings

The Irish NEEAP energy savings figures are based on a combination of technical calculations and empirical evidence. The methods and assumptions used are detailed in Annex 2 of the 2009 NEEAP report [35]. The savings due to the introduction of the building regulations are based on an assumed percentage improvement relative to the theoretical energy consumption of equivalent dwellings constructed to the 2002 regulations. Assumptions are made on numbers of new dwellings occupied and the future floor area of the stock. A transition phase for the uptake of the regulations is included assuming 0% compliance in houses completed in year 1, 25% in year 2, 75% in year 3 and 100% in year 4. Savings projected from existing retrofit measures such as the warmer homes scheme

[1] Note, the NEEAP accounts for policy measures from 2007-2016. In limited circumstances measures introduced pre 2007 that generate additional savings in the period 2007-2016 can be included. On this basis energy savings accruing due to the application of the 2002 building regulations on dwellings newly constructed post 2007 are accounted for.

(addressing fuel poverty) are based on previous programme experience. Savings from proposed future measures, such as the Home Energy Savings Scheme, are estimated based on heat flow model calculations, the results of which are reduced by 20% to account for potential rebound effects [35].

2.3 Methodology.

Energy demand modelling has been classified *inter alia* by Weyant and Hill (1999) [9], Canes (2002) [10] and Huntington and Weyant (2004) [11]. One major division typically identified is between so-called ‘top down’ models which are typically based on macroeconomic social accounting matrices, and ‘bottom up’ models which can describe in greater detail the expected impact of changes in technology or input costs within particular product markets. Despite the distinction being widespread, the two categories of bottom-up and top-down aren’t mutually exclusive, there also exists a “hybrid” class where the two approaches are combined; one of the main contributions of the hybrid approach is the detection of missing information and dynamics that simple top-down or bottom-up models cannot detect on their own [13]. The distinction is still useful however to highlight in broad terms the differences between the two types of approach.

Top-down models are relatively easy to develop due their low input data intensity. The high level econometric data is widely collected, in standard format over long historical time periods and readily available. For the residential sector the data includes energy prices, population, number of households, disposable income, etc. By their nature they are ideal for market based analysis of energy consumption trends, for analysing the long term effects of fuel and technology costs and the effectiveness of market based policy initiatives such as tax breaks and financial incentives, which can be modelled as reduced costs. Using econometrics based on historical data and trends as a basis for estimating future consumption has the advantage that the model may be calibrated to give results consistent with past experience. The corresponding disadvantage is that it is less able to deal with future scenarios that exhibit fundamental changes relative to past experience. Also, the disadvantage of an econometric, market based approach is that it cannot explicitly model the impacts of purely technical measures.

Bottom-up models on the other hand have a high input data intensity. The large amounts of low level data can be difficult to obtain, in many cases because it has never been historically collected in an organised manner, or in other cases because the necessary data is private, such as individualised household energy bills. Detailed data on floor area, levels of insulation, space and water heating shares, boiler characteristics, etc. are required for modelling residential sector energy demand. The strength of the bottom up approach is its potential to model the effects of new energy technologies, which may produce step changes to patterns of energy consumption and for which general historical trends cannot be used as an indication of future performance. The disadvantage of a technology focused model is that it is less able to deal with factors heavily affected by human behaviour in response to price or income changes.

Swan & Ugursal have carried out a full review of the various different types of energy models employed in the residential sector [12]. They describe the bottom up engineering method as a model which " *relies on information on the dwelling characteristics and end uses themselves to calculate the energy consumption based on power ratings and use characteristics and/or heat transfer and thermodynamic principles.......This technique is used to broadly classify the housing stock according to vintage, size, house type, etcetera. It is possible to develop archetype definitions for each major class of house and utilize these descriptions as the input data for energy modeling. The energy consumption estimates of modeled archetypes are scaled up to be representative of the regional or national housing stock by multiplying the results by the number of houses which fit the description of each archetype.*"

Aydinalp-Koksal & Ugursal [16] compare a range of bottom-up modelling approaches, pointing to modelling based on an engineering approach [36], neural networks [37] and conditional demand analysis [38]. Aydinalp-Koksal & Ugursal conclude that each approach has its own advantages and disadvantages. They point to a difficulty with the engineering method in the inclusion of consumer behaviour and other socio-economic variables that have a significant effect on the residential energy use. However, because of the high level of detail and flexibility provided by engineering based models, they can be used to evaluate the impact of a wide range of scenarios for energy efficiency on residential energy demand, which is the focus of this paper. This is not to ignore the importance of behaviour in particular and this will be the focus of subsequent analysis for Ireland as appropriate data becomes available.

2.3.1 Existing UK and Irish energy models

In developing the proposed model it is useful to first consider how the same issue has been approached by other EU member states. In practice, models currently in use at the national and international level tend to be purely top-down or top-down with bottom up modules or components to deal with specific issues.

The UK government energy model, known as the DECC, BERR or DTI model, is top down partial equilibrium model of the UK energy market. Energy demand is modelled by a system of over 150 econometric relationships to historical fuel demands, with the impact of current efficiency measures being explicitly included using complementary bottom up modules. The residential final energy demand is driven by real personal disposable income, domestic energy prices, number of household, external temperature and uptake of major appliances. These top-down forecasts are then adjusted to take into account bottom-up engineering modelled energy savings specific to UK residential sector energy.[39].

The earliest such bottom-up model was the Building Research Establishment Housing Model for Energy Studies, or BREHOMES. The model incorporates over 1000 dwelling categories to define historical housing stock and an average dwelling to predict future trends in the overall stock [40]. It uses the Building Research Establishment Domestic Energy Model (BREDEM) which is a heat flow model based on heat transfer of the building envelope. The energy demand for lights and appliances is calculated exogenously and is specified at an aggregated level. BREHOMES uses various data sources but the major input data were from market research surveys. This approach of establishing a limited set of dwellings intended to represent classes of houses found in the residential sector and applying the bottom up engineering method to simulate energy consumption is known as the archetype method [12]. Ireland’s national energy forecasts are generated in a similar way to that in the

UK, i.e. by adjusting the output of a top-down econometric model with modelled bottom-up energy savings [8].

2.3.2 Modelling approach adopted.

In comparing the suitability of top-down and bottom-up models for the residential sector, Swan and Ugursal conclude that top down models "….*do not provide an indication of the potential impacts of* [energy efficiency] *technologies and are therefore not helpful in the development of policy or incentive to encourage them.*" They further state that "*If the objective is to evaluate the impact of new technologies, the only option is to use bottom-up* [engineering method] *techniques. This is a point of emphasis because compared to taxation and pricing policies, technological solutions are more likely to gain public acceptance to reduce energy consumption and associated greenhouse gas emissions.*"

The emphasis in the Irish NEEAP is on measures pointing to technology based solutions to increasing energy efficiency in the residential sector e.g. building regulations, rather than direct fiscal instruments, e.g. fuel taxing. This can clearly be seen in the proposed measures for achieving the targeted savings in the Irish NEEAP, as shown in Table 2.1. This then suggests that the bottom-up engineering method is the most suitable approach for modelling energy consumption in a residential sector affected by significant improvements in energy efficiency technologies. This mirrors the conclusion of Hull et al (2009) [29]. As mentioned, the bottom up method will need further refinement to incorporate behavioural and socio-economic impacts as necessary.

2.3.3 Structure of model

The work done can be considered in two parts. The first is a model of the space and water heating energy demand of new dwellings using an archetype approach. The second is work done external to the archetype model as an initial step in creating a detailed bottom up model of the entire residential sector, of which the work presented here is a first stage.

The archetype model of new dwellings is used to calculate the theoretical space and water heating demand of new dwellings constructed between 1997 and 2020. Note that historical data on energy consumption of the Irish residential sector used in this model was limited to the period up to 2006. Therefore *future* energy demand scenarios in this paper start from 2007, which allows the model to capture the pre- and post-2008 period when there was a significant change in building regulations. The principal outputs from the archetype model are the results for new dwellings constructed in the period 2007 to 2020. These are used to model the space and water heating demand of houses built in this period and to build scenarios which quantify the impact of energy efficiency savings due to the introduction of the 2008 and 2010 building regulations. The 1997 to 2006 results from the archetype model are used for another purpose, namely to check the accuracy of the approach against historical data and to analyse the energy efficiency performance of the 1997 stock of dwellings between 1998 and 2006.

In order to move from a model of space and water heating in new dwellings to a more general model of the residential sector as a whole, which is more useful for assessing total energy demand and for comparing the results with those used in the national energy forecasts, two more elements are needed, i.e. an estimation of the energy consumption of the stock of dwellings existing as of 2007 going forward to 2020 and of the energy demand of cooking, lighting and electric appliances for existing and future houses. Full bottom up modelling of either of these aspects is outside the scope of this paper and left for further work. Instead, more simple analysis can be carried out and yields useful results.

In summary, the approach adopted here is as follows: The archetype model is used to model space and water heating of dwellings constructed from 2007. Space and water heating for dwellings built prior to 2007 are modelled by extrapolation based on historical trends. This includes the historical trend for change in energy efficiency of space and water heating in existing dwellings, which is estimated by decomposing the energy consumption of the stock of dwellings between 1997 and 2006 into that of the 1997 stock and the dwellings newly occupied dwellings between 1998 and 2006. Finally, the future energy demand of cooking, lighting and appliances is estimated by extrapolating from the historically observed trend to observed saturation levels achieved elsewhere.

2.4 Archetype model of space and water heating for new dwellings

2.4.1 Archetypes

The first step in developing an archetype model of the residential sector is to establish a set of dwelling archetypes that adequately characterise the dwelling stock being considered. Typically this is done broadly by categories such as age band (often corresponding to the introduction of particular building regulations) building type (in many EU studies a simple distinction between single and multi-family dwellings is used) construction type (e.g. cavity wall versus non-cavity) etc. As the purpose of this analysis is to examine the effect of successive improvements to the building regulations the author choose to characterise dwellings by dwelling type and by the building regulations to which they are built to. Four editions of the building regulations and five dwelling types were modelled, as discussed in the following sections.

Having established a set of archetypes the next step is the model their energy consumption using the engineering method i.e. based on technical factors, e.g. floor area, area of glazing, U-value of walls etc, and then extrapolate this to give the consumption for the residential sector as a whole. Therefore a technical model of the energy demand for individual dwellings is required. The Dwelling Energy Assessment Procedure, or DEAP, is the official Irish procedure for calculating and assessing the energy performance of dwellings and is used in this model to estimate the energy performance of a number of selected archetype dwellings [41].

2.4.1.1 Heat loss model

DEAP was developed by the Sustainable Energy Authority Ireland (SEAI) as a tool to demonstrate the compliance of new dwellings to part L of the building regulations, governing the conservation of fuel and energy, and to produce Building Energy Rating (BER) labels and reports, as required by the Energy Performance of Buildings Directive (EPBD) [42]. The DEAP calculation framework is based on IS EN 13790[43], and draws heavily on the calculation procedures and tabulated data of the UK Standard Assessment Procedure[44]. The procedure takes account for space heating, water heating and lighting, as well as reduction in imported energy due to sustainable energy generation technologies.

The calculation is performed using a software tool which requires as inputs a detailed description of the building envelope and heating system and which outputs energy consumption split into a number of end uses. The technical guidance documents accompanying the building regulations contain minimum requirements which were used as inputs to the DEAP model. Within the software data is entered under a number of headings, e.g. dimensions, ventilation, building elements etc. A brief description of the inputs and outputs under each heading is given in Appendix B.

It must be noted that although the DEAP software outputs results for pumps & fans and lighting, the archetype model is only used to calculate the space and water heating energy requirement for new dwellings, therefore only the main and secondary space and water heating end uses were used. The electrical energy demand of lighting and appliances is considered separately and so the figures for the energy consumption of pumps & fans and lighting output from DEAP are not used within the residential energy model.

2.4.1.2 Building regulations

The 2005 technical guidance document to part L of the building regulations [45] lays out a set of minimum requirements for a range of building elements to comply with. Overall compliance is demonstrated by ensuring the CO_2 emissions associated with the dwelling, as calculated by DEAP, do not exceed a target value which is specified in the technical guidance document, and calculated by DEAP, known as the Maximum Permitted Carbon Dioxide Emission Rate (MPCDER). Typically, meeting each of the individual minimum performance requirements for each building element will be enough for the dwelling to achieve overall compliance.

The 2008 building regulations aim to achieve a 40% cut in energy consumption of newly built dwellings over dwellings built under the previous 2005 regulations. The accompanying technical guidance document [46] lays out a set of minimum requirements for various building elements, but these new requirements are either the same as or only sight improvements on those in the 2005 regulations. Therefore compliance cannot be met by simply sticking to these minimum elemental requirements. To demonstrate compliance the overall primary energy consumption of the dwelling is calculated in DEAP and compared to that of a reference dwelling, also calculated in DEAP. The ratio of these consumptions is the Energy Performance Coefficient (EPC). In order to comply with the regulations, the EPC has to be less than the Maximum Permitted Energy Performance Coefficient (MPEPC). In the 2008 regulations, the MPEPC is 0.6, ensuring the 40% reduction on 2005 levels required. In what areas and the extent to which the minimum requirements are exceeded in order to meet the overall requirement is left up to the individual builder. Therefore DEAP was used only to model dwellings meeting the 2005 regulations, and the total energy demand of dwellings meeting the 2008 and 2010 regulations was calculated by applying the MPEPC to the equivalent 2005 dwelling, with the improvements to specific building elements not being explicitly defined. The inputs and assumptions used for modelling dwellings in accordance with the 2005 building regulations are given in Appendix C

In addition to an overall reduction in energy consumption, the 2008 regulations also specify a minimum level of energy which is to be provided from on site renewable energy sources [47]. This requirement can be complied with by providing either 10kWh/m^2/annum water heating, space heating or cooling, or 4kWh/m^2/annum electricity, or an equivalent combination of the two. The lower requirement for electricity is due to the relatively low efficiency of electricity supply (currently approx 40% in Ireland). As well as contributing to the renewable energy target, solar thermal, solar PV and wind generated electricity also count towards reducing the primary energy demand, and therefore help contribute to both targets.

At the time of the finalisation of the new 2008 building regulations, it was also announced that further regulations would be introduced in 2010 to further reduce energy consumption in the home, this time by 60% of the consumption of homes built under the 2005 regulations. At the time of modelling no technical guidance document or detailed information was yet available. In order to predict household energy consumption under these regulations the same basic model was used as for the 2005 and 2008 regulations, but in this case an MPEPC of 0.4 was applied. It is also assumed that the as the energy savings requirement is increasing from 40 to 60%, the renewable energy requirement would increase also, from 10kWh/m^2/annum to 15kWh/m^2/annum.

2.4.1.3 Application of 2008 and 2010 building regulations

Having calculated the energy savings required to meet the 2008 and 2010 building regulations through application of the MPEPC, it was next necessary to distribute these savings across the different end-uses. The exact distribution of these savings is not specified in the regulations and is left up to the builder/designer in each case. It is clear that the majority of the savings would have to be achieved in space heating, followed by water heating. The following assumptions were made for this paper:

- The energy consumption for lighting is halved in 2008 with no further improvement in 2010, in accordance with standard DEAP calculation for the savings due to conversion to low energy lighting, as laid out in Appendix L of the DEAP Manual[48]
- With regard to the (relatively small) energy consumption of pumps and fans, in the absence of any particular policies or technologies to increase the energy efficiency of these devices the author assumed the energy consumption would remain unchanged.
- With regards to water heating energy demand, it was assumed that efficiencies could be improved on in the areas of distribution, storage and primary energy conversion. Potential efficiency measures such as more efficient use of hot water, i.e. reduced service demand or a heat recovery system from used hot water were not considered. From the DEAP analysis it was taken that distribution, storage and primary energy conversion losses add to approximately 1500 kWh/annum for a house and 1000 kWh/annum for an apartment. It was assumed that for the 2008 regulations there could be a 40% reduction in energy loss here and 60% under the 2010 regulations. These reductions were not based on detailed analysis of the heat loss and energy savings potential from the water distribution system, rather it was a simplistic assumption mirroring the scale of the energy savings required across the dwelling as a whole.
- As the regulations also make allowance for the reduction in imported primary energy through on-site generation using renewable energy technologies, it was assumed that half of the renewable energy target would be met by some form of renewable energy source that could count toward reducing the water heating primary energy requirement, e.g. solar thermal. This assumption leads to a 5kWh/m^2/annum and a 7.5 kWh/m^2/annum reduction in water heating requirement under the 2008 and 2010 regulations respectfully. This assumption was not based on detailed analysis of the fraction of water heating energy demand that could be achieved through renewable energy

sources, rather it was a simplistic assumption used to allocate renewable energy between the space and water heating end uses.

- The energy savings from distribution, storage and primary conversion, along with the reduction in demand through the use of on-site renewable generation add to give the total reduction in primary demand assumed possible from the water heating sector. When this, along with the savings from lighting, pumps and fans are accounted for, the remaining energy savings required to meet the balance, which was in all cases the majority, were necessarily assumed to be provided from space heating.

2.4.1.4 Dwelling types

The author also chose to model a number of different dwelling types. Data on the stock of permanently occupied dwellings was available from the Central Statistics office for two census years, 2002 and 2006, split by 4 dwelling types (detached, semi-detached, terraced, apartment). Data on the number of dwellings completed annually was available from the Department of the Environment split by five dwelling types (bungalow, detached, semi-detached, terraced, apartment) from 1994 to 2004 and split by three dwelling types from 2005 to 2007. This data is given in Appendix D. The author chose to utilise the highest disaggregation of data available and so used the 5 dwelling types used by the Department of the Environment from 1994 to 2004, bungalow (referred to here as one storey detached), detached (referred to here as two storey detached), semi detached, terraced and apartment.

The main cause of difference in energy consumption between building types, all other factors being equal, is the difference in exposed fabric area and glazing. For example a two storey semi-detached house will have one less wall exposed to the unheated surroundings compared to a two storey detached house of the same size, and therefore the former will be more efficient. The floor area of a dwelling is also a major influencing factor on energy efficiency. The energy consumption per dwelling was modelled in DEAP for a range of different floor areas and there was found to be a linear relationship between the two, though not directly proportional, for example a doubling of floor area would not lead to a doubling of energy consumption. Therefore for each dwelling the formula of the line relating floor area to energy consumption was established.

2.4.1.5 Modelling 1997 and 2002 building regulations

As well as examining the current and future building regulations in order to model the behaviour of new dwellings constructed in the future, the previous regulations were also modelled in order to analyse the behaviour of the stock of existing dwellings, and attempt to quantify the energy efficiency improvements that may be made by the existing stock in the future. There was very little change in the regulations between 2002 and 2005, with the minimum required elemental U-values staying the same [47]. Therefore for the purpose of this model the authors have assumed no difference between the 2002 and the 2005 regulations. There were significant changes between the 1997 and 2002 regulations, with large improvements in the minimum required U-Values [49] Therefore dwellings from this period were modelled separately in DEAP.

2.4.1.6 DEAP outputs

Figure 2.1 shows the result of the DEAP analysis for energy consumption of each of the standard dwelling types under the 2005 building regulations, expressed as kWh/m^2/annum. Shown in Figure 2.2 is the predicted decrease in energy consumption under the new building regulations, broken down by end-use for a single storey detached house and an apartment. The requirement for the majority of the 60% total energy savings to be achieved from space heating due to the limited scope for improvement in the other end uses has the greatest impact in those dwellings such as apartments which are inherently more efficient with regards to space heating in the base case, compared to dwellings such as detached houses which are inherently less efficient space heating wise and thus have greater scope to achieve reductions. For example for a one storey detached house, achieving an overall 60% energy saving requires 63% savings in space heating, with the share of space heating reducing from 79% of the DEAP energy consumption under the 2005 regulations to 73% under the 2010 regulations. For an apartment achieving overall 60% energy savings requires 74% savings in space heating, with the share of space heating reducing from 56% of the DEAP energy consumption under the 2005 regulations to just 37% under the 2010 regulations, with water heating now accounting for 49% of total DEAP energy demand in this scenario.

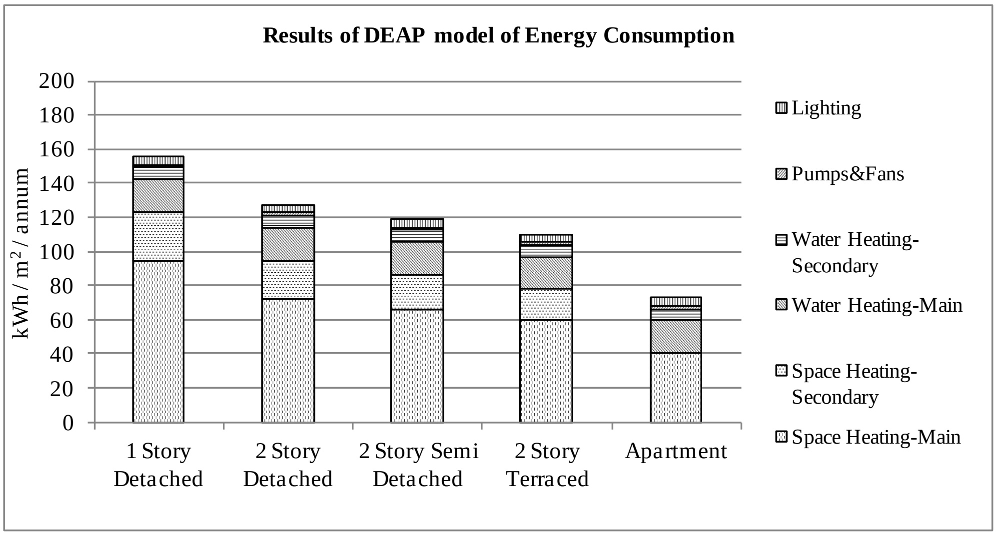

Figure 2.1: *Results of DEAP model of Energy Consumption*

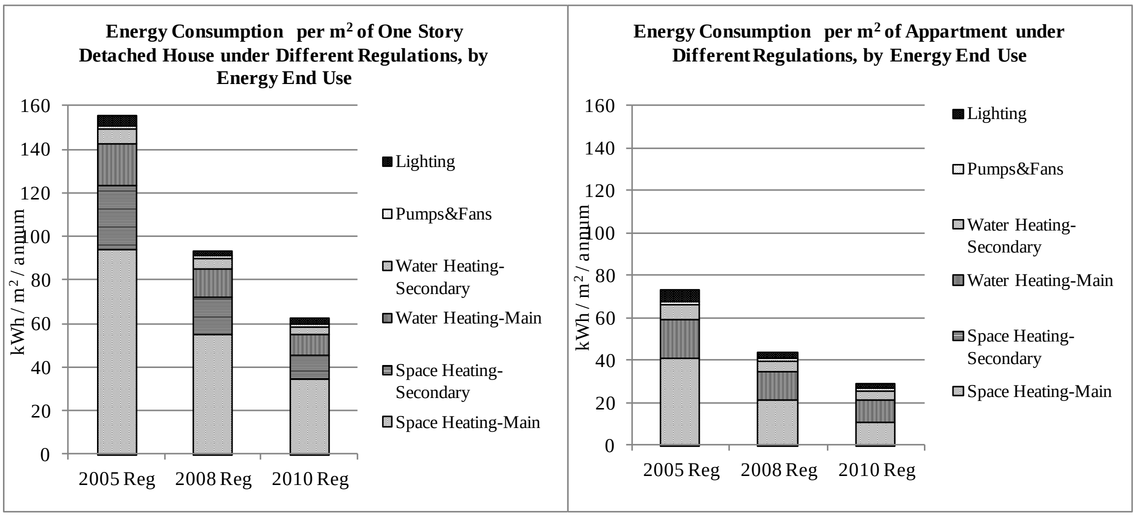

Figure 2.2: *End Use Energy Consumption of One Story Detached House and Apartment under Different Building Regulations*

2.4.2 Numbers of newly occupied dwellings

Having modelled the energy demand of the range of archetype dwellings under different building regulations, it is necessary to forecast the annual quantities of each entering the stock of occupied dwellings. Previous forecasts of the numbers of occupied dwellings in the national stock were based on predictions of population growth and the occupancy ratio of dwellings, which in the long term at least are the two principal drivers. The recent downturn in Ireland’s property market and the freezing of credit, however, has delivered a fundamental shock to the system and created a short to medium term step change in the demand for new dwellings. As the time horizon for the model is 2020 these short to medium term effects will have a significant impact and so must be taken into account. To do this the historical data regarding the supply and demand of new dwellings needs to be examined.

2.4.2.1 Data on housing stock

Data on the annual numbers of new dwellings completed is available from the Department of the Environment, Heritage and Local Government (DoEHLG), and is based on Electricity Supply Board (ESB) data from electricity grid connections to newly built dwellings [50]. Historical data from 1994 to 2007 for numbers of detached houses, scheme houses and apartments are shown in the first half of Figure 2.3. Scheme houses here accounts for semi detached and terraced dwellings. It can be seen that the most striking trend is the surge in the numbers of scheme houses completed between 2001 and 2006, representing the boom period in household construction. During this period 22% of the total housing stock existing in 2006 was built.

The demand for dwellings is taken to be the increase in the numbers of dwellings in the stock of permanently occupied dwellings plus the number of dwellings required to make up for demolition and obsolescence of the existing stock. A certain portion of the extra supply over and above the demand for permanently occupied dwellings goes to meet the demand for holiday homes and second residences. The remaining excess in supply over demand will enter into the stock of vacant dwellings.

Data on the national stock of permanently occupied dwellings, the numbers of vacant dwellings and the numbers of holiday homes are collected by the Central Statistics Office (CSO) in the national census [3]. The number of vacant dwellings more than doubled in the four year period between the last two census dates in 2002 and 2006 from 104,000 to 216,000 dwellings. Overall there has been an accumulation of 137,000 vacant dwellings between 1994 and 2006, 112,500 of these arising between 2002 and 2006. As well as the numbers of overall dwellings the breakdown by dwelling type is also required. This data is again provided by the CSO but is only available for the last two survey years, 2002 and 2006. Using this data the split in all other years is assumed using simple linear interpolation and extrapolation. This area requires further analysis that falls beyond the scope of this paper.

Data on the rate of obsolescence is not gathered directly. A report by DKM Economic Consultants for Davy Stockbrokers issued in 2003 [51] notes that there is a lack of data in this area, but estimates that the obsolescence rate is thought to be in the region of 0.5% of the stock of occupied dwellings annually. Instead of direct observation, the obsolescence rate can be back-calculated by comparing the data available on numbers of dwellings completed, numbers of occupied dwellings and numbers of vacant dwellings. Using this method the DoEHLG estimates the annual rate of obsolescence as 0.73% of the stock of occupied dwellings. This figure is used in this paper, and was assumed to remain constant between 1990 and 2020. Using this rate, the number of newly occupied dwellings each year was established, that is, the net increase in the number of occupied plus the number of dwellings that were built to replace demolished or obsolete stock

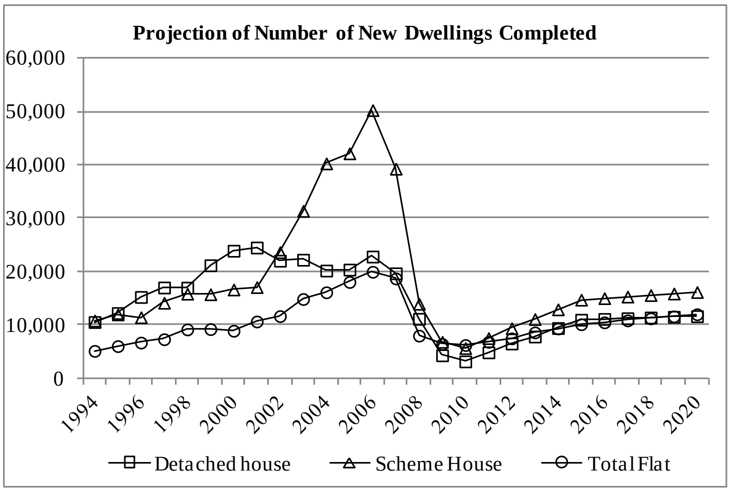

Figure 2.3: *Projected numbers of new dwellings completed.*

2.4.2.2 Projection for vacant dwellings and newly completed dwellings

The best estimate available for the likely short term performance of the residential construction sector comes from the ESRI's spring 2009 quarterly economic commentary [52][1]. ESRI's analysis estimates that the number of dwelling completions would be 17,500 in 2009 and 15,000 in 2010. It was assumed in the model that in the period 2009-2012, 25% of the back log of vacant dwellings that occurred between 1994 and 2006 would be cleared, and that in the period 2013 to 2020 a further 45% would be cleared, bringing the total to 70%. Finally, it was assumed that after a low in 2010, the

[1] This paper was originally submitted for peer review in 2009 and accepted 2010. At the time of modelling 2009 was the most up to date data available. The author has not subsequently updated the model with more recent data, but for this thesis has provided where relevant more up to data statistics to compare with the model projections for the initial period 2009-2012.

numbers of dwellings becoming newly occupied, which is equivalent to the numbers newly completed plus newly cleared from the stock of vacant dwellings, would increase to a sustainable level of 45,000 units per annum in 2015 and 50,000 in 2020. Excluding dwellings occupied from the stock of vacant dwellings this results in an estimated 35,800 new dwelling completions in 2015 rising to 39,800 completions in 2020. For comparison Irelands 2009 NEEAP estimates 45,000 new dwellings completed per annum in the period 2015 to 2020. This is in line with long term predictions based on population growth and occupancy ratios. Further information on the housing demand in Ireland is given in Appendix E. The results of these assumptions for the numbers of dwellings completed and newly occupied are given in Figure 2.3 and Figure 2.4.

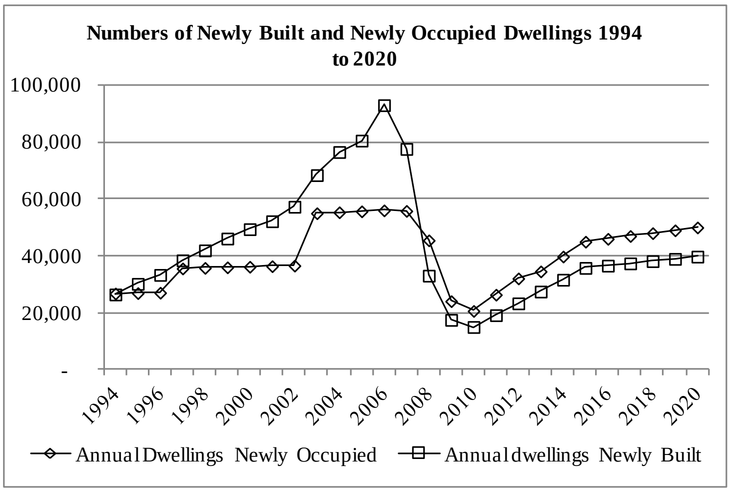

Figure 2.4: *Projected numbers of newly built and newly occupied dwellings*

2.4.2.3 Floor area

Data on floor areas was provided by the SEAI and is based on planning permission statistics gathered by local government authorities. These were then projected forward using linear regression. At the time of modelling data up to 2006 was available. This data is shown in Appendix F. It should be noted that the floor areas for newly constructed dwellings in Ireland are at the upper end of the spectrum of typical EU floor areas. In the fourth quarter of 2006, the last year for which historical data was available at the time of modelling the average new house for which planning permission was sought had a floor area of 161m^2, the average apartment was 82m^2, while the average detached house was

227m^2. For comparison Appendix F provides data from the 2010 Housing Statistics in the European Union report which gives what data is available on floor areas across EU member states [5].

2.4.2.4 Timing of building regulations applying to newly occupied dwellings

The rate of penetration of dwellings built to a new building regulation into the stock of occupied dwellings from the year in which it comes into force will depend on the number of new houses being built, the rate of transition to the new regulations and how they are superseded by subsequent regulations. The regulations affecting the energy consumption of future newly occupied dwellings are the 2008 and 2010 regulations. In order to investigate historical trends the 1998 and 2002, 2005 regulations are also examined. However it must be noted that for the purposes of this model the 2002 and 2005 regulations are considered to be the same.

When the 2002 building regulations were introduced, it was stipulated that where planning permission had been applied for before the regulations were introduced, builders would have a further three years to complete the building before the new requirements would be mandatory[47]. It was assumed therefore that 25% of dwellings in 2002 were built to the new regulations, 50% in 2003, 75% in 2004 and 100% in 2005. As 2002 regulations are considered the same as 2005, the next ones introduced are the 2008 regulations. These have a shorter introductory period than the previous set. In this case, dwellings which were granted planning permission before the introduction of the regulations have only one year to substantially complete the dwelling before the new regulations will apply, i.e. have the external walls built to roof level by July 09 [46]. Therefore in this case a faster adoption rate of 25% in year 1, 75% in year 2 and 100% in year 3 was assumed. The same rate of penetration was assumed for the 2010 regulations.

It was assumed that the stock of vacant dwellings have been built to the 2002/2005 building regulations. This assumption is made even though the accumulated total of vacant dwellings used is counted back to 1994, and is felt to be valid for two reasons. Firstly, the majority of the accumulation occurred between 2002 and 2007 and secondly, of the dwellings that are counted from before 2002, it can be assumed that a portion of these will have actually become occupied at a later year, and their place on the vacant stock taken by dwellings constructed to the later regulations. Combining all of these assumptions with the new dwelling projections shown in Figure 2.4 gives the result shown in Figure 2.5

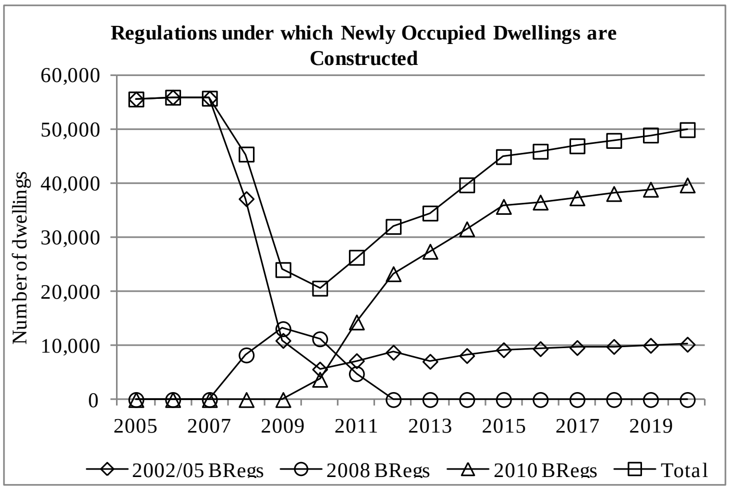

Figure 2.5: *Projected numbers of dwellings built to different building regulations*

2.4.2.5 Non-compliance and behavioural effects

The techno-economic model of the energy consumption of newly occupied dwellings developed here takes into account the theoretical increase in energy efficiency due to improved building regulations, but there are two major reasons why the theoretical potential is unlikely to be realised. These are non-compliance with the building regulations and the effects of human behaviour.

Historically non compliance may have occurred through deliberate cost saving measures (such as installing less than the required thickness of insulation) or poor workmanship (for example problems with thermal bridging due to incorrect construction details around lintels, cills and jams). Future issues of non-compliance are likely to result from the fact that simply meeting the minimum building element requirements as before is no longer sufficient to achieve the MPEPC. Little information on the extent or effects of non-compliance is available and the area is currently poorly understood, although the growing databases of Building Energy Ratings for new and existing dwellings will allow for some improvement here.

Behavioural factors include the autonomous increasing of comfort levels and what is termed the take back or rebound effect, in which efficiency gains from technical improvements are offset by increased service demand (for example increased internal temperatures recorded in dwellings post energy efficiency retrofit works [53-55]) . The rebound effect has been estimated to account for a loss of 10-30% of the total technical energy savings for space heating and 10-40% for water heating [21, 56-58].

In the past behavioural effects have resulted in increased internal temperatures and the move from living room heating to whole house heating associated with the increasing penetration of central heating. Between 1990 and 2006 the penetration of central heating increased from 58% to 91%. Information on internal temperatures is not available for Ireland but data from the Building Research Establishment in the UK suggests that internal temperatures have risen by approximately 1.5 degrees from 16.5 to just over 18 degrees centigrade between 1990 and 2004 [7, 59]. The former trend would be expected to slow down in the next 10 year period as the penetration of dwellings with central heating asymptotically approaches 100%, though it is less certain what scope remains for increasing internal temperatures.

A full analysis of the potential scale of non compliance and the scope for take back due to behavioural effects specifically in the context of Ireland and the proposed building regulations is outside the scope of this paper and is left for further work. The results presented here do not include for these effects and so can be considered as the technical energy savings potential of the measures.

2.5 Estimations and assumptions external to archetype model

2.5.1 Residential sector energy demand

As discussed in section 2.3.3, as a first step in creating a more general model of the residential sector, a simple analysis of space and water heating energy demand in existing dwellings and the energy demand of lighting and electrical appliances was carried out and is presented here.

2.5.2 Estimate of space and water heating energy demand of existing stock

Work done by the authors to date has not attempted to build a complete archetype model approach towards the stock of existing dwellings due to its heterogeneous nature. However, the authors do make an estimate of the energy demand of the stock of dwellings existing in 1997 between 1998 and 2006 as follows: The historical trend in improvement of existing dwellings was assessed by taking the observed energy consumption of the residential sector between 1997 and 2006 and subtracting the theoretical consumption of the cumulative new dwellings built from 1998 to 2006, as calculated using the DEAP model described previously. This difference is assumed to give the trend in the performance of the 1997 stock and is used to estimate future energy efficiency improvements of existing houses. The results when applied to space heating are shown in Figure 2.6. It can be seen from Figure 2.6 that the efficiency of newly constructed dwellings improves significantly in the time period, primarily due to the coming into effect of the 2002 building regulations. Table 2.2 shows a sample calculation of the space heating energy demand of newly constructed dwellings in 2005 based on data from the bottom up archetype model described previously.

Overall energy efficiency trends have been assumed to be the result of two competing factors: technical factors which tend to increase energy efficiency and non-technical factors (occupant behaviour, non compliance with building regulations etc) which tend to reduce it. Using this assumption, all observed increases in efficiency are assumed to be the result of purely technical efficiency gains. The highest efficiency calculated for space heating in the 1997 stock was in 2002, representing a 5.09% improvement on 1997 levels. This was assumed to be the technical improvement over the whole period, giving an annual average improvement between 1997 and 2006 of 0.58%. In the case of water heating no overall efficiency improvement was observed, therefore it was assumed there was no technical efficiency improvement.

	2005 New Dellings			
	Num newly built	Floor Area	Space Heating	
			kWh/annum	kWh/m2
1St Det	6,480	207	24,105	116
2St Det	13,961	207	17,624	85
Semi D	20,821	121	11,949	99
Terrace	3,395	121	10,789	89
Apparment	11,354	78	3,721	48
Weighted Average		144	13,032	86

Table 2.2*: Sample calculation of space heating energy consumption of new dwellings in 2005*

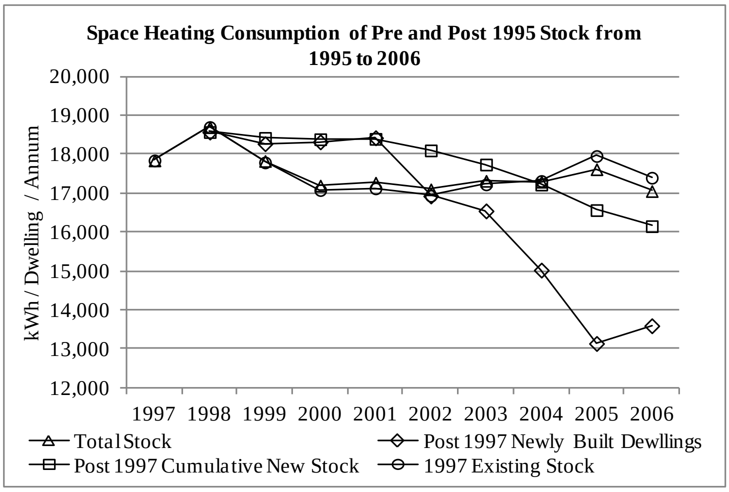

Figure 2.6:*Space heating consumption of pre and post 1995 stock of occupied dwellings between 1995 and 2006*

2.5.2.1 Obsolescence

Since the number of newly occupied dwellings takes into account the number of dwellings rebuilt to replace those lost due to obsolescence, the stock of existing dwellings has to be correspondingly reduced annually by an amount equal to 0.73% of the previous year's total stock.

2.5.2.2 Need for further work

This model has attempted to quantify the historical trends toward increased efficiency and assumed that these would continue as before. There is a wide scope for much more detailed modelling in this area. Possible future government initiatives and grants to encourage retrofitting will play a major role. In the NEEAP the government has proposed that 29% of the saving necessary to meet the 2016 target for energy reductions in the residential sector should come from improvements in the existing stock

[33]. More information on the exact nature of the proposals for improvement in this area are needed before more detailed modelling can be carried out.

2.5.3 Forecasted energy demand for lighting, electric appliances and cooking

DEAP is designed to calculate the energy efficiency characteristics governed by the construction of the dwelling itself, and not by the specific energy consumption behaviour of the inhabitants themselves. Therefore DEAP does not take into account the overall energy consumption of cooking and electrical appliances, though as discussed in Appendix B, DEAP does assume a certain level of heat gains from the operation of electric appliances within the dwelling which serve to reduce the overall space heating energy demand. These are based simply on an the floor area of the dwelling rather than on appliance ownership or usage data.. As for the analysis of space and water heating energy consumption of existing dwellings, a full bottom up model has been left for further work, and instead a more simple estimate is used in order to progress. This estimate of electric appliances energy consumption made here has not been linked back into the DEAP model with respect to the heat gains, for example an estimated increase in appliance usage does not result in increased heat gains from appliances in the bottom up archetype model portion of the model. Cooking is considered separately from lighting and electric appliances as it consumes more than one fuel type and in future analysis it will be convenient to consider the electricity consumption of lighting and electric appliances separately. The energy demand for lighting, electric appliances and cooking was calculated as an average of the entire stock and is not split into existing dwellings and newly occupied dwellings.

2.5.3.1 Lighting and appliances

Energy consumption of electrical and electronic appliances has in particular been steadily rising both in absolute terms and relative to the other energy end-uses which have been improving in efficiency, and is therefore important to consider in terms of the future energy demand of the residential sector. Figure 2.7 shows the historical and projected trends for the electricity consumption of lighting and appliances. The historical trend is based on the data supplied by the SEAI on residential sector energy consumption by fuel type. The lighting and appliances consumption was assumed to be the remainder of the total electricity consumption minus the electricity consumption for space heating, water heating and cooking.

The reasons for the increase in consumption are assessed in an SEAI report on historical energy trends in the residential sector [7]. It identifies the increase in penetration of a wide range of electric appliances and also the increase in size of televisions, refrigerators, freezers etc. Although there is uncertainty regarding the growth rates of penetration on new appliances, it has been assumed that the increasing trend in electricity demand per household will continue until a certain saturation level is reached. In this paper, it is assumed that the trend will tend towards 3500 kWh per dwelling per annum, as per Figure 2.7. This level was chosen based on figures for the electricity consumption of appliances in other EU countries [60]. A more detailed separate bottom up model for this demand curve is required, but this was outside the scope of this report and is left for further work[1].

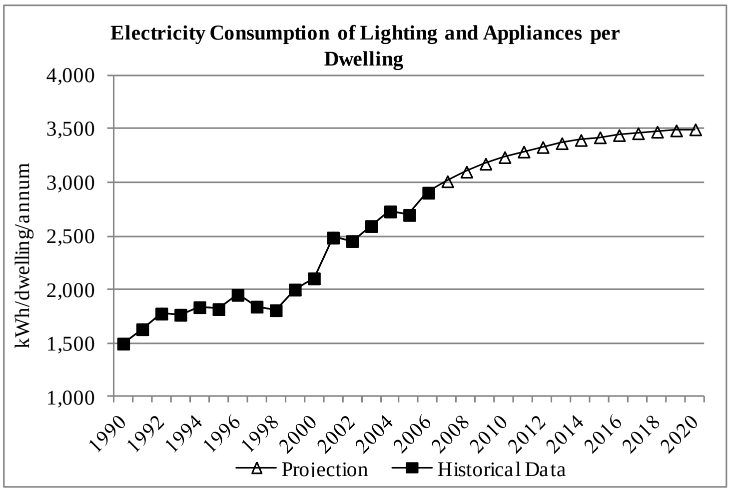

Figure 2.7: *Energy Consumption of Lighting and Appliances*

2.5.3.2 Cooking

The energy consumption of cooking is also derived from the SEAI assumptions of end use energy consumption. Data is given for the energy consumption for cooking in 2003, and it was assumed that the energy consumption rate per dwelling rate remained constant from 1990 to 2006. This

[1] In their most recent report on Energy in the Residential Sector; 2013 Report, SEAI points to a lack of data on electricity end use as a key data gap. For that report they estimated the electricity consumption of lighting and appliances to be 2,806 kWh/dwelling/annum in 2011. The report shows that although total electricity consumption per dwelling in the residential sector rose 22% in the period 1990 -2011 from 4,112 to 5,022 kWh/dwelling/annum, in the period 2005 to 2011 insignificant growth was recorded and in 2011 consumption reduced by 5.3%

consumption is 830 kWh per dwelling per annum. It is assumed here that the consumption per dwelling will continue to remain constant at this rate until 2020.

2.6 Results

2.6.1 Energy demand of newly occupied dwellings

Having modelled the energy consumption of a representative set of newly built dwellings, and the trends in the numbers, types and building regulations of newly occupied dwellings in the future, the next step is to combine these two to give an overall model of the energy consumption of newly occupied dwellings.

The result of the DEAP modelling provides a set of figures for energy consumption for each end use, for each dwelling type, for each building regulation, for a range of floor areas. The DEAP outputs were mains and secondary space heating and mains and secondary water heating. Firstly, the predicted floor areas for each year were taken account of by interpolation from the range of floor areas tested in DEAP. This gave a list of energy consumptions per end use, per dwelling type, per building regulation, for each year, at the predicted floor area. Multiplying each of these energy consumption values by the percentage share of each dwelling type and of each building regulation, and then summing, gave the energy consumption for water and space heating of an average newly built dwelling in a given year. Factoring in the buildings added from the stock of vacant dwellings gave the energy consumption of an average newly occupied dwelling.

The total energy consumption for the cooking and lighting & appliances end uses was calculated in terms of the consumption of an average dwelling in the stock in the first place, and so these were added to the average space and water heating consumptions per dwelling as calculated above to give the total energy consumption per dwelling.

Figure 2.8 shows the theoretical energy consumption of an average newly built dwelling from 1997 to 2020. The figures for 2007 to 2020 were used to predict the performance of newly occupied dwellings in that period and the figures for 1997 to 2006 were used to estimate the performance of the existing stock in that period. The reduction in space heating demand is the most prominent trend. According to the model it accounted for 70% of household energy consumption in newly built dwellings in 1997, down to just under 60% in 2006 and is predicted to fall to 27% by 2015. The end use with the biggest gains is lighting & appliances, which rose from 7% of total energy consumption in newly built homes in 1996, to 12% in 2006 and is estimated to rise to 29% by 2020. Unfortunately historical data on the residential energy demand by end use for new dwellings is not available for direct comparison. The historical data on the breakdown by end use for the stock as a whole shows that space heating accounted for 80% in 1990 and 68% in 2006.

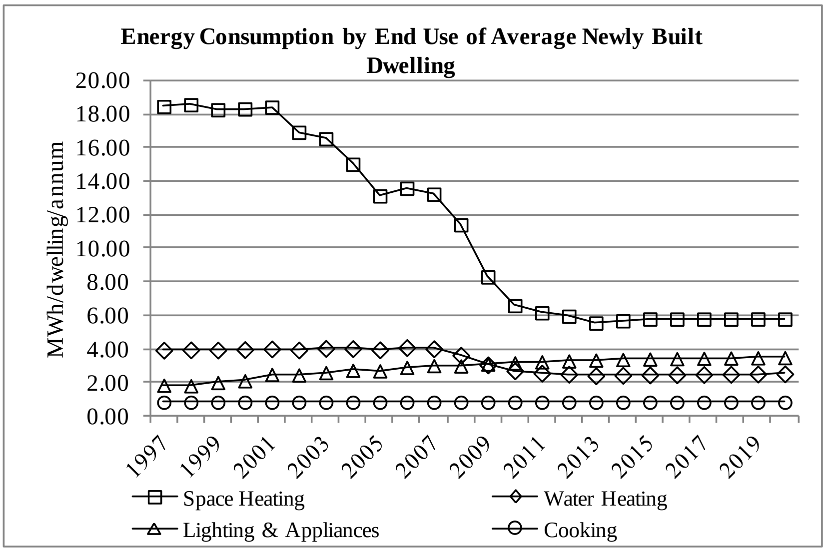

Figure 2.8: *Energy Consumption of Average Newly Built Dwelling 1997-2020*

2.6.2 Overall results of residential model

To examine the energy demand of the residential sector as a whole three scenarios were created. The first is a baseline scenario, which assumes that all houses that become occupied from 2007 to 2020 are built to the 2005 regulations, and there is no improvement in the efficiency of the 2006 stock of occupied dwellings in that time. Here residential energy demand is projected to grow by 18% in the period 2007 – 2020 from 37,286GWh to 44,310GWh. The second is the building regulations scenario. This assumes the introduction of the 2008 and 2010 building regulations and also assumes that there will be no improvement in the efficiency of the existing 2006 stock in till 2020. The projected energy demand in 2020 is 3,547 GWh less than the baseline, indicating an 8.0% saving in energy demand in

2020. The final scenario is the building regulations plus retrofitting scenario, which assumes the application of the 2008 and 2010 regulations and also an annual improvement in the 2006 stock of occupied dwellings in line with the historically observed trend. This shows a further saving of 1,721 GWh or 3.9% with respect to the baseline. Figure 2.9 compares the three scenarios.

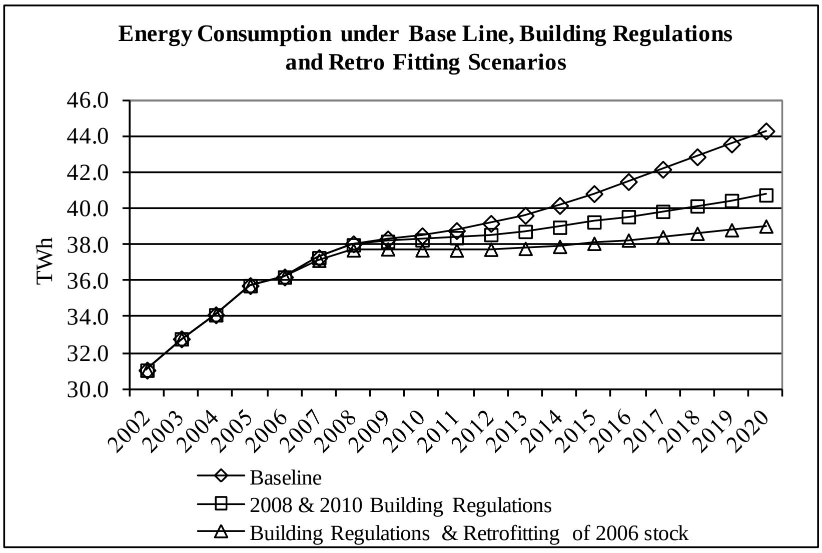

Figure 2.9: *Residential Energy Demand Under Different Policy Scenarios*

2.6.2.1 Back casting to verify model accuracy

In order to verify that the model was giving sensible outputs, it was used ex-post to estimate energy demand from 1997 to 2006, taking into account the introduction of the 1997 regulations. The results are shown in Figure 2.10. The bottom up model is seen to overestimate the energy efficiency gains in the period. There are a number of potential reasons for this. The first is that the bottom up model does not take into account rebound effects due to occupant behaviour. The model also assumes 100% compliance with the 1997 regulations in 1998 and 100% enforcement thereafter. Finally the historical data has been climate corrected which can lead to spikes in the corrected consumption in exceptionally warm years

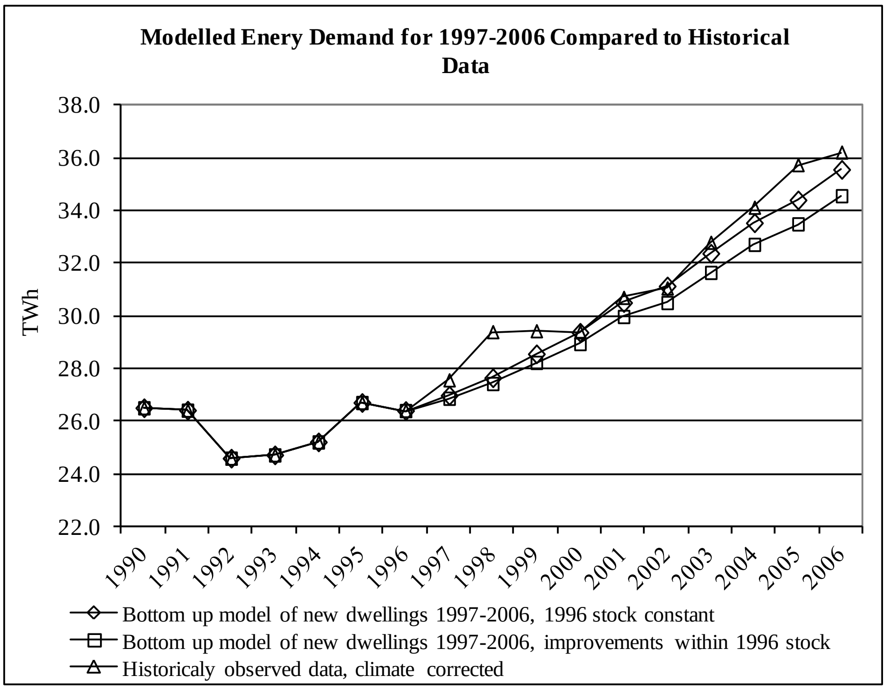

Figure 2.10: *Comparison of Bottom Up Model to Historical data 1997 - 2006*

2.6.2.2 Comparison with national energy forecasts and national energy efficiency action plan.

Ireland's national energy baseline forecasts are developed using a top down econometric model of the residential energy sector, based on ESRI's HERMES macro-economic model of the Irish economy [8]. The national energy forecasts also contain a policy scenario corresponding to meeting energy efficiency and renewable energy targets set in the Government White Paper on Energy [61]. Figure 2.10 compares the national energy baseline scenario and white paper scenarios and the results based on the bottom-up model developed in this paper. The base line projections to 2020 of both approaches are similar, while it can be seen that the savings required to meet the white paper target are more than expected from the 08 & 10 building regulations and autonomous retrofitting alone, which is reflected in the NEEAP as shown earlier in Table 2.1. The NEEAP estimates savings due to the introduction of the 2008 and 2010 building regulations as 3,590 GWh, or 309 ktoe. This is in close agreement with the archetype model figure of 3,547 GWh, or 305 ktoe.

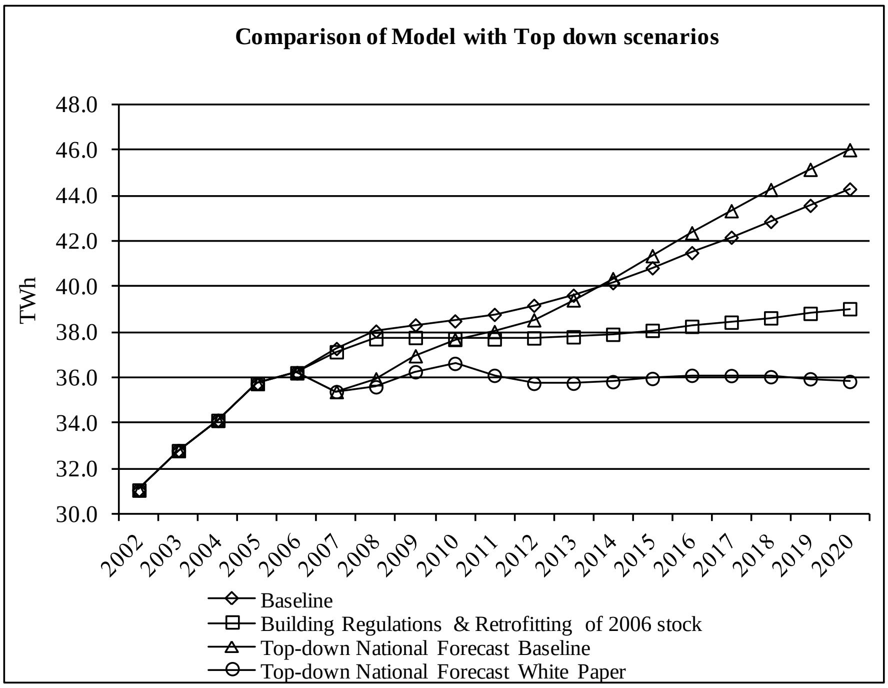

Figure 2.11: *Comparison with National Energy Forecasts*

2.6.2.3 Quantifying effects of the property bubble on the effectiveness of new building regulations

The recent boom in the Irish property market resulted in 23% of permanently occupied dwellings in 2008 being constructed between 2002 and 2008 and 34% between 1997 and 2008. As well as this, between the last two census dates in 2002 and 2006 there was an increase in the number of vacant dwellings from 104,000 to 216,000. These will in future become occupied at the expense of dwellings that would otherwise be newly constructed to later, improved building standards. This model assumes that 70% of the number of vacant dwellings accumulated between 2002 and 2006 will become occupied between 2008 and 2020, accounting for 22% of total newly occupied dwellings in that time. If instead all dwellings newly occupied between 2008 and 2020 were newly built to the relevant standard (2008 or 2010 regulations) it would result in savings of 814 GWh in 2020, or 1.8% relative to the baseline scenario shown in Figure 2.9.

The introduction of the 2008 building regulations coincided with the bursting of this property bubble. The resulting dramatic slowdown in construction activity will reduce their effectiveness in delivering energy savings. It is possible to estimate the increased effect that similar improvements would have had were they introduced in time to affect the dwellings constructed during the boom. For example, had the standards introduced in 2008 been instead introduced in 2002, there would have been additional savings of 2,768 GWh in 2020 or a further 6.2% reduction in demand relative to the baseline. A summary of the energy savings in 2020 arising from the policy scenarios and due to the bursting of the property bubble discussed above is given in Table 2.3.

Scenario	GWh	% savings on Baseline
Total energy consumption of residential sector in 2020 in baseline scenario	44,310	
Savings from 2008 and 2010 building regulations	3,547	8.0%
Savings from the autonomous retrofit of existing dwellings	1,721	3.9%
Savings had there been no vacant dwellings in 2008	814	1.8%
Savings had the 2008 regulations been introduced in 2002	2,768	6.2%

Table 2.3: *Summary of savings in 2020 from bottom-up model scenarios*

2.7 Conclusions

This paper develops an archetype model of the energy consumption of new dwellings in the Irish residential sector and uses it to calculate the future energy savings due to the introduction of the 2008 and 2010 building regulations. The projected energy savings due to the introduction of 2008 and 2010 building regulations agree with the projections given in the National Energy Efficiency Action Plan. The DEAP modelling has shown that the new building regulations will require significant improvement in space heating efficiency. Modelling of the housing stock has shown that the delayed entry of currently vacant dwellings built to older regulations into the stock of occupied dwellings will reduce the potential for energy efficiency gains through the introduction of new building regulations.

The retro fitting of existing stock will be required to play a large part in meeting energy efficiency targets. This model does not address the need for bottom-up modelling of the potential improvements to be gained in this area. Neither does it attempt to quantify the likely rebound effect that will apply to the theoretical technical energy efficiency improvements calculated using the bottom up method. Further work is also required in modelling electricity use for lighting and appliances.

Chapter 3

3 Improved modelling of thermal energy savings potential in the existing residential stock using a newly available data source.

Abstract

This paper presents a bottom up approach to modelling the energy savings potential of energy efficiency improvement measures to be applied through retrofit of the existing dwelling stock. The model uses 175 archetype dwellings that focus on three key dwelling characteristics, namely building type, energy performance and notably, wall construction type. It takes advantage of newly available, rich dataset on the construction characteristics of the 2011 housing stock in Ireland. This data enables analysis based on wall construction type that was not previously feasible. While Ireland is the focus, this approach is applicable to any EU Member state for which data on dwelling characteristics exists from surveys carried as part of Energy Performance Certificate calculations mandated by the Energy Services Directive. The results quantify the impact of a range of different retrofit measures on the different residential dwelling archetypes. In addition, sensitivity analysis is performed on the effects of internal temperature and direct rebound effects on the energy savings that may be realised. The results of this paper are in the form of disaggregated potential energy saving values which will lead to further work on scenario based modelling of different government policies and programmes.

Keywords: Archetype, Residential, Retrofit

3.1 Introduction

This paper presents a bottom up approach to modelling the energy savings potential of energy efficiency improvement measures to be applied through retrofit of the existing dwelling stock. It utilises new EU energy performance certificate survey data using Ireland as a case study. This rich dataset provides detailed data on the construction characteristics of a large (18%) sample of the 2011 housing stock. Using this data we establish a set of 175 archetype dwellings to represent the breadth of dwellings existing in the stock. We base the archetypes on three key dwelling characteristics, namely building type, energy performance and notably, wall construction type. Data from the Central Statistics Office (CSO) 2011 national survey is used to scale this dataset up to the national level. This set of detailed data on the physical characteristics of each archetype dwelling are then used as inputs to a building physics model of the energy consumption of dwellings. The model used is the Dwelling Energy Assessment Procedure (DEAP) model, developed by SEAI to produce Energy Performance Certificates (EPC), also known in Ireland as Building Energy Ratings (BER), in accordance with the EU Energy Services Directive (ESD). This is then used to model the energy savings accruing from a number of potential energy savings retrofit measures. This approach is equally applicable to any EU state for which data exists on dwelling characteristics, either as part of surveys carried as part of EPC calculations as mandated by the EPBD, or through other sources. Examples of EU member states which produce energy performance certificates based on kWh/m2/annum figures, the same format as are used in this model, include Austria, Belgium, Czech Republic, Finland, France, Germany and Luxembourg. This model builds on previous work by the authors on a bottom up model of the energy consumption of space and water heating of newly occupied dwellings from 2009 to 2020 [62] as well as previous estimates of retrofit savings potential and an estimation of the electricity consumption of lighting and appliances of all dwellings from 2009 to 2020 contained within the LEAP_Ireland model [25, 63].

The layout of this paper is as follows: Section 1 provides the context for modelling the impacts of energy efficiency retrofit measures on future residential sector energy demand, describing the policy background driving modelling at EU and national level and a literature review of the various modelling approaches adopted by others; section 3.2 presents the modelling methodology adopted and the data used in this work; section 3.3 describes the archetype dwellings developed; section 3.4

discusses the data used to scale the model to the national level; section 3.5 covers the numbers of dwellings retrofitted by archetype and section 3.6 covers the energy savings calculations. Section 6 presents the results obtained for the baseline projection and section 7 draws conclusions and discusses the limitations of the approach taken, pointing to further research areas and work to be done to potentially improve the accuracy and functionality of the analysis.

3.1.1 International and national policy context

Energy efficiency at the EU level is promoted through the ESD[28] and, for the built environment in particular, through the Energy Performance in Buildings Directive (EPBD)[42]. In the Irish context SEAI in conjunction with the Department of Communications Energy and Natural Resources (DCENR) has run a number of schemes aimed at encouraging energy efficiency retrofit works for existing dwellings in the Irish residential sector. Past examples include the Home Energy Savings Scheme (HESS) and the Warmer Homes Scheme. 2011 saw the introduction of “Better Energy: The National Upgrade Programme”[64] which superseded all previous energy retrofit programmes, both residential and non-residential, and which set the objective of delivering energy efficiency upgrades to one million residential, public and commercial buildings by 2020. The branch of Better Energy focusing on the residential sector is known as “Better Energy: Homes” (BEH).

3.1.2 Bottom up modelling

A full review of the various different types of energy models employed in the residential sector has been carried by Swan & Ugursal[12]. Models are broadly classified as either top down or bottom up. The modelling approach adopted here is the bottom-up engineering archetype model, which lends itself to analysing policy measures that have a technical focus such as building regulations or retrofitting. Kavgic et al[19] also describe the principles of bottom up residential energy consumption models and go on to give an overview of four models, each with distinct characteristics, focusing on residential building stocks in Canada, Finland, USA and Belgium. They also provide a more detailed examination and comparison of a further five bottom up residential models from the UK. Kannan and Strachan also provide a summary of UK housing stock models[65]. Mata et al list and compare features of seventeen residential building stock models as well introducing their own ECCABS model which they use for the Swedish residential sector[66, 67].

There are a number of limitations associated with this approach as identified in the literature. Giraudet et al [68] consider that energy consumption is the resulting product of technical factors affecting energy efficiency (the amount of energy per unit of energy service) and behavioural factors affecting energy sufficiency (the amount of energy service). They note that purely technical models fail to take account of sufficiency feedbacks, also known as the rebound effect. Similar findings are made by Cayre et al [14], Cayla et al [15], and Kelly [18]. Aydinalp-Koksal & Ugursal[16] point to a difficulty with the engineering method in the inclusion of consumer or occupant behaviour and other socio-economic variables that have a significant effect on the residential energy use, but note that in spite of this "*because of the high level of detail and flexibility provided by engineering based models, they can be used to evaluate the impact of a wide range of scenarios for energy conservation on residential energy consumption and GHG emissions*". Natarajan et al [17]again review existing building stock modelling techniques and make distinctions between deterministic versus probabilistic modelling as well as equation based modelling versus agent based modelling. They identify the shortcomings of deterministic, equation based, building physics models, including their inability to endogenously account for occupant behaviour and also the fact that most deterministic models do not capture uncertainty surrounding input variables. While levelling the above criticisms at building physics models Natarajan et al also note that "*they are very useful in identifying a baseline technical potential for future emission reductions."*

While acknowledging the limitations of such an analysis, in particular with respect to behavior and rebound effects, the authors conclude that the bottom up engineering approach is still capable of producing models which yield valuable insights, particularly in establishing the technical savings potential of energy efficiency technologies. This paper develops a bottom-up engineering archetype model of the Irish residential sector to estimate the technical savings potential of BEH. It does not account for behaviour feedbacks and other causes of the rebound effect at this time, but we fully acknowledges the importance of quantifying this effect and leave this for further work. As such it can be considered that this work presents an upper bound on savings potential under each of the scenarios considered.

3.1.3 Previous Ireland residential sector energy modelling

Much work has been done for the UK residential sector with the production of many well documented residential energy consumption models. Less has been published in terms of models specific to the Irish residential sector but some significant work has been done. Clinch and Healy published a number of papers in the early 2000's investigating the potential both for energy savings and to a greater extent the potential to alleviate fuel poverty in Ireland due to retrofit of the residential dwelling stock[69-74]. Two studies have been carried out by Hull et al[29] and Rogan et al [75] focusing the drivers behind natural gas consumption in Ireland based on actual metered data. Ahern et al[76] created a bottom up model of detached, oil centrally heated dwellings and used it to investigate the economic and carbon case for thermal retrofit measures. Scheer et al [77] conducted an ex post billing analysis of 210 dwellings that had undergone retrofit work under the HESS to quantify the actual energy savings achieved. The Economic and Social Research Institute (ESRI) has carried out econometric modelling of Irish residential sector energy use, much of it focused on appliance ownership and usage with some recent work on the value placed by consumers on building energy efficiency [78-81]. This paper presents bottom up archetype model similar to work published by Ahern et al. Where it adds to the literature is in making use for the first time of a new data base, and using this data to take into account explicitly the wall construction type as an important parameter governing the retrofit options available to archetypes and that likelihood of a particular archetype dwelling undergoing retrofit .

3.2 Methodology and data sources

3.2.1 Overview

The first step in developing an archetype model of the residential sector is to establish a set of dwelling archetypes that adequately characterise the entire dwelling stock. For each archetype dwelling we then calculate both the number of retrofits and the energy savings potential for a number of retrofit measures. The former can be considered the activity level and the latter the intensity level for each archetype [82]. The total energy savings equal the product of the number of dwellings retrofitted by the energy savings per retrofit, summed across all retrofit measures and across all archetypes. This is summarised by the bottom up equation:

$$E_y = \sum_{A,M} N_{A,y} \times S_{A,M},$$

Equation 1

Ey = Energy Savings in Year y

$N_{A,y}$= Number of dwellings of archetype A retrofitted in year y

$S_{A,M}$ = Energy Savings per annum for retrofit measure M carried out on archetype dwelling A

A=For each archetype

M = For each retrofit measure carried out

3.2.2 Main data sources

A rich dataset of the construction characteristics of each archetype was required for the analysis. We made use of the National BER research tool which provides detailed data on the construction characteristics of the current housing stock. BER certificates were introduced in Ireland in 2007 as required by the ESD. The BER rates the technical energy performance of domestic dwellings, assigning each a rating from A1-G based on a calculation of their primary energy consumption in kWh/m^2/annum. It is a legal requirement for all dwellings being sold or rented in Ireland to have a BER. The BER calculation is carried out using the DEAP. This procedure and associated software were developed by the SEAI to demonstrate the compliance of new dwellings to part L of the building regulations, governing the conservation of fuel and energy, and to produce BER labels and reports. The DEAP calculation framework is based on IS EN 13790[43] and draws heavily on the calculation procedures and tabulated data of the UK Standard Assessment Procedure[44]. The procedure takes account of space heating, water heating, ventilation and lighting calculated on the basis of standard occupancy, heating patterns, internal temperature etc, as well as reduction in imported energy due to sustainable energy generation technologies[83, 84]. It is performed using the DEAP software tool which requires as inputs a detailed description of the building envelope and heating system and which outputs energy consumption split into a number of end uses.

The results of every BER carried out as well as the large amount of data collected on the physical characteristics of each dwelling required for the associated DEAP calculation are stored by SEAI in what is known as the National Administration System (NAS) database. The full list of data fields available is given in Appendix B. As of mid 2012 this BER database contained details of approx 300,000 dwellings, out of a total dwelling stock of 1.6 million. This NAS data has been made publicly available for research purposes through the National BER Research Tool, hosted on the SEAI website[85]. This is a live database and is updated regularly. The version downloaded by the authors in August 2012 thus represents a snap shot at that time and at which point it contained 304,814 entries. This frozen dataset was used for all analysis carried out in this paper.

We apply filters to this raw data set along a number of criteria in order to remove outliers and any nonsensical or erroneous values. The filters applied were developed by Rogan[75] in collaboration with SEAI as part of earlier work using a similar dataset. The full list of filters applied is given in Table 3.1. Post filtering the number of entries remaining was 253,875. This data was supplemented with data from the 2011 census from the CSO [3], data on the rate of obsolescence from the Department of Environment, Heritage and Local Government [86].

Variable	**Filter**
TypeofRating	Provisional
DwellingType	House
GroundFloorArea	<30; >1000
Terrace/SemiDet GroundFloorArea	>500
HSMainSystemEfficiency	<20%
HSEffAdjFactor	<0.7
HSSupplSystemEff	/=Null, 0, <19%
HSSupplHeatFraction	/=Null, 0, 0.1, 0.15, 0.2
WHMainSystemEff	<20%, >450%
WHEffAdjFactor	<0.7
DeclaredLossFactor	>20
LivingAreaPercent	<5%, >90%
ThermalDridgingFactor	<0, >0.15
Negative Energy Values	All

Table 3.1: *Filters applied to NAS data*

3.3 Archetypes

3.3.1 Overview

The challenge in establishing a set of dwelling archetypes that adequately characterise the entire dwelling stock lies in the highly heterogeneous nature of existing dwellings which have widely differing construction characteristics. Existing dwellings have been constructed across a time horizon of over a hundred years, to a wide variety of building practices and regulations, with dwellings even of the same vintage having had differing degrees of retrofit improvement work already carried out or having fallen into differing degrees of disrepair. We also need to consider the fact that certain forms of retrofit work may not be economically or physically possible to carry out in certain dwelling types, particularly relating to wall construction type. To address these issues we classified dwellings by three main characteristics; building type, energy label and wall construction type.

3.3.2 Building type

We first split the existing stock by building type. Some building types are inherently more efficient than others due to the difference in fabric area exposed to non-heated spaces. For example a semi-detached dwelling will have one less wall exposed to the unheated surroundings compared to a detached dwelling of the same size, and therefore the former will be more efficient, all else being equal. Building type also tends to influence floor area, which effects total energy consumption.

The NAS database classifies dwellings by 10 building types, as shown in Table 3.2. Detached refers to dwellings that have no walls adjoining another dwelling or heated space. Semi-detached refers to dwellings that have one wall adjoining a heated space. Mid-terraced refers to dwellings with two walls adjoining heated spaces, though End of terrace refers to dwellings with one wall adjoining a heated space. We first altered these categories by merging all apartment types into one category along with Maisonettes. End of terraced dwellings and semi detached were merged into one category as both are considered to have one wall adjoining a heated space. Basement dwellings accounted for a negligible percentage of the total (0.005%) and so were ignored. This initially reduces the number of categories to 5. If we then also separately consider the number of stories for each category, this gives a total of 25 building types, though the majority of these have a share of less than 1% and can be neglected. Figure 3.1 shows each building type as a percentage of the total NAS sample. Of these we identify 5 building types which account for 87% of all dwellings. These are 2 storey semi-detached, 1 storey apartment, 2 storey detached, 2 storey terraced and 1 storey detached. We assume that these 5 building types are representative of all dwellings within the stock. Therefore all detached dwellings greater than 2 storey are represented as 2 storey detached, all apartments are represented as 1 storey apartments and all terraced are represented as 2 storey terraced dwellings.

NAS Categories	**Simplified Building Types**	**% in NAS**	
Detached house	Detached house	25.6%	25.6%
Semi-detached house	Semi Detached house	28.0%	35.0%
End of terrace house		7.1%	
Mid-terrace house	Terraced house	14.6%	14.6%
Apartment	Apartment	1.7%	24.7%
Ground-floor apartment		6.3%	
Maisonette		1.0%	
Mid-floor apartment		9.0%	
Top-floor apartment		6.6%	
Basement Dwelling	Deleted	0.0%	0.0%

Table 3.2: *Reduction in dwelling categories from NAS to model.*

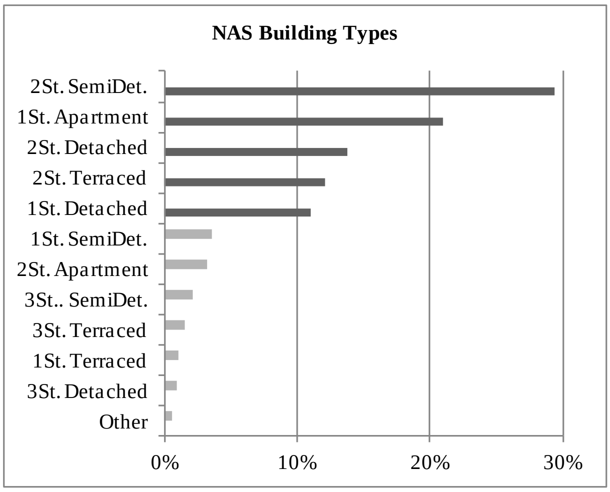

Figure 3.1: *Building types in NAS database*

3.3.3 *Energy performance band*

The NAS database classifies all dwellings into BER bands expressed in kWh primary energy/m^2/annum and we use this data to further classify the dwelling stock within the model. The 15 energy bands for each BER label are specified in Statutory Instrument 66 of 2006[87] and are shown in Table 3.3**.** We condense these 15 bands down to 7 by ignoring the subdivisions of 1/2/3 and instead considering bands of A, B, C, D, E, F and G. This was done to reduce computation and also to ensure larger sample sizes per band from the NAS database.

NAS	Label	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	E1	E2	F	G
	kWh/m^2/annum	<25	>25	>50	>75	>100	>125	>150	>175	>200	>225	>260	>300	>340	>380	>450
Model	Label	A			B			C			D		E		F	G
	kWh/m^2/annum	<75			>75			>150			>225		>300		>380	>450

Table 3.3: *BER bands expressed in kWh/m^2/annum*

3.3.4 Wall construction type

Standard wall construction practices in Ireland have changed over the years both due to autonomous improvements in standard practice and since the 1970's due to the introduction of and improvements to the building regulations. As a result a range of wall construction types are prevalent in the existing dwelling stock. The wall construction type of a dwelling is an important consideration in terms of what retrofit measures are possible to implement and what improvement in energy performance is possible. This is point is expanded upon in section 3.5.1.

We broadly consider just two main divisions in wall types. These are cavity wall and solid wall construction. Cavity wall refers to a wall consisting of two separate masonry leaves, separated by cavity. This cavity can by completely hollow, as in the case of early un-insulated cavity walls, can have a layer of solid insulation between the leaves, attached to the inside leave but separated from the outer leaf, as in the case of the more recent practice of insulated cavity walls, or can be completely filled with insulating foam or beading, as is common when retrofitting an un-insulated cavity wall. All other types of wall construction which do not consist of two separate masonry leaves and which includes solid brick, solid block, hollow or cinder block, mass concrete or timber frame dwellings, we class as solid wall construction. Solid walls can be un-insulated, as in the case of older dwellings, or insulated with either internal or external solid wall insulation.

Although “Wall Construction Type” data for each dwelling is recorded and stored on the NAS database, it is one of a number of fields stored on the NAS which is not publicly available on the National BER Research tool. While this means that the data cannot be extracted or inspected on the level of individual records, it is still possible in limited circumstances to request SEAI to run specific, targeted database queries on the full NAS database that can yield useful information on this field.

Wall U value data is readily available so as a first step in classifying the dwelling stock by wall type we considered the typical wall U value of the various wall construction types. Note that U value is measured in W/m^{2}K but henceforth in this paper U values will be given as unit less numbers for convenience. Based on the default wall U values for each wall type specified by DEAP, and contained in Table S3 of the DEAP manual[48] we made the assumption that all dwellings with a wall U value of ≤0.6 would likely be either insulated cavity wall or insulated solid wall, all dwellings with a wall U value >1.78 would likely be un-insulated solid wall and all dwellings with 0.6<U value ≤1.78 would be a mixture of un-insulated cavity wall and partially insulated solid wall. To test this assumption we requested the NAS database administrators to run a query that would provide the breakdown of dwellings in each of those wall U value bands by wall construction type. The results are shown in Figure 3.2. The NAS database has 10 wall construction type categories. Two of these, “Blank” and “Other”, we ignore. Two more, “300mm Cavity” and 300mm Filled Cavity” we class as cavity wall. The remaining six NAS categories, “225 Solid Brick”, “325 Solid Brick”, “Stone”, “Concrete Hollow Block”, Timber Frame” and “Solid Mass Concrete” we group together as solid wall.

Dwellings with a wall U value of ≤0.6 are a mix of solid and cavity wall types but we assume that in all cases they are insulated as it is not seen as plausible that a U value that low could be achieved otherwise. As the majority of dwellings surveyed in the NAS (79%) have wall U value of ≤0.6 it was sensible to further divide this category, so based on the data we establish a further division of U value < 0.38. These latter dwellings are labelled Highly Insulated Wall (HIW) dwellings, while dwellings with wall U Value of 0.38≤U≤0.6 are referred to as Insulated Wall (IW) dwellings.

The U value band 0.6<U≤1.78 also consists of a mixture of cavity and solid wall. Here we assume that all dwellings in this U value band which are recorded as either 300mm cavity or 300mm filled

cavity are in fact Un-Insulated Cavity Walls (UICW). This assumption is based on the fact that the default U value for an insulated cavity wall within DEAP is 0.6 and that it is unlikely that insulated cavity dwellings would have a recorded wall U value higher than this. To differentiate solid wall dwellings in this band from those in the U>1.78 band we refer to them as Partially Insulated Solid Wall (PISW), as it is likely that they have some degree of internal insulation in order to achieve such a U value, though obviously not fully insulated, as are those in the U≤0.6 band. Using these criteria 58% of dwellings in the 0.6<U≤1.78 band are PISW, 40% are UICW and 2% are other. We ignore the "other" category and make the simplifying assumption that the 60% are PISW and 40% UICW. The crucial difference between these two archetypes is that during retrofit UICW can have cavity wall insulation installed whereas PISW cannot. Other than that, because they both account for the same wall U-value range their physical characteristics are determined by the same set of NAS entries and they will have the same energy consumption in the base case and show the same savings for retrofit measures other than wall insulation.

According to the results 98% of dwellings with wall U value >1.78 were classed as solid wall confirming our initial assumption on this. For the model we make the simplifying assumption that 100% of these dwellings are Un-Insulated Solid Walls (UISW).

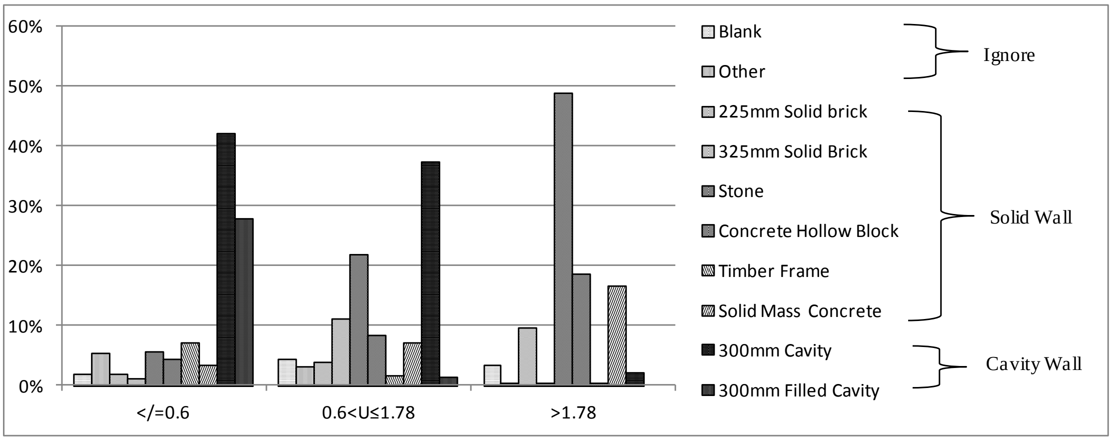

Figure 3.2: *Wall construction type by U-value band according to NAS database*

3.3.5 Archetypes Summary

To summarise, the criteria chosen to classify the existing dwelling stock were 5 dwelling types, 7 energy ratings and 5 wall construction types which give 175 archetype dwellings, as per Table 3.4.

5 Dwelling Types	7 Energy ratings	5 Wall Construction Types	Archetypes
1 Storey Detahced	A	Un-Insulated Solid Wall	
2 Storey Detached	B	Partially Insulated Solid Wall	
2 Storey Semi Detached	C	Un-Insulated Cavity Wall	
2 Storey Terraced	D	Insulated Wall	175 Archetypes
1 Storey Apartment	E	Highly Insulated Wall	
	F		
	G		

Table 3.4: *Dwelling archetypes*

3.4 Scaling of NAS data to national level.

Next it was required to scale up the NAS data to be representative of the whole dwelling stock. To do this we calibrated it with CSO 2011 census data. In order scale up the data to be representative of the entire dwelling stock we use the CSO 2011 census data. The CSO data gives a breakdown of the 2011 housing stock by 9 age groups and 4 building types. When compared to the CSO data it was found that in terms of age the NAS data was weighted towards newer dwellings and in terms of building type it was weighted towards apartments and away and from detached dwellings. This is to be expected as the requirement for a BER was originally for newly constructed dwellings only and is currently for any dwellings for sale or rent or in receipt of a retrofit grant. Figure 3.3 shows the NAS sample size as a percentage of the total CSO figure for detached houses, apartments and for the total stock, in each time period (the other building types are omitted for clarity). To give the breakdown of archetype dwellings in the total stock in the base year, 2011, the NAS data was scaled up to match the recorded CSO data in terms of age category and building type. Figure 3.4 shows the shares of dwellings by building type and age group both in the NAS database and from the CSO data. The shares of dwellings by BER and wall construction type from the NAS are also shown. The dwelling shares in the model match those in the CSO for building type and age group and match NAS values for BER and Wall type.

It should be noted that as we do not have data from the CSO on BER or wall construction type we cannot say if the scaled up NAS data is representative with respect to these parameters. We suspect that the NAS data for pre 2001 dwellings may well be biased towards IW dwellings, as anyone availing of a HESS or BEH grant is required to get a BER after works have been carried out, and a large percentage of these dwellings had cavity wall insulation installed, as will be discussed in the following section. In communication with experts from SEAI it was suggested that the above analysis may result in an overestimation of the proportion of dwellings in the UICW category. To attempt to investigate these issues further we looked at relevant data from the National Survey of Housing Quality 2001/02(NSHQ), an analysis of which is presented in Appendix G. Unfortunately we were unable to draw any further conclusions from this data set due to the large amount of uncertainty amongst respondents regarding the wall construction type. For example of respondents who knew they had at least some cavity walls 34% did not know whether or not these were insulated. In the absence of further data required to investigate this matter further, and in light of the fact that the NAS data is the most up to date and comprehensive data that is currently available the authors propose that the results of this analysis are a best estimate of the upper bound of UICW dwellings available for retrofit. The potential effect of lower than predicted numbers of UICW dwellings available for retrofit is best assessed by setting a lower bound and using scenario analysis to investigate the sensitivity of the results to this variable.

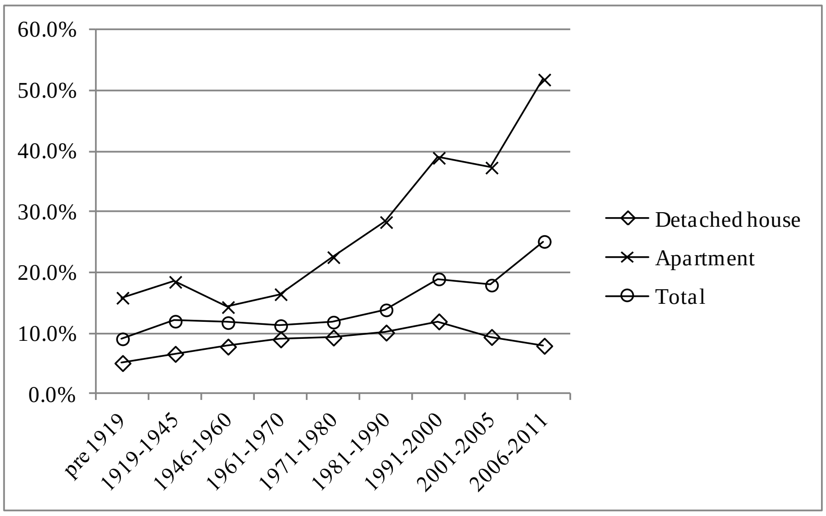

Figure 3.3: *Percent sample of the CSO figure represented in the NAS database.*

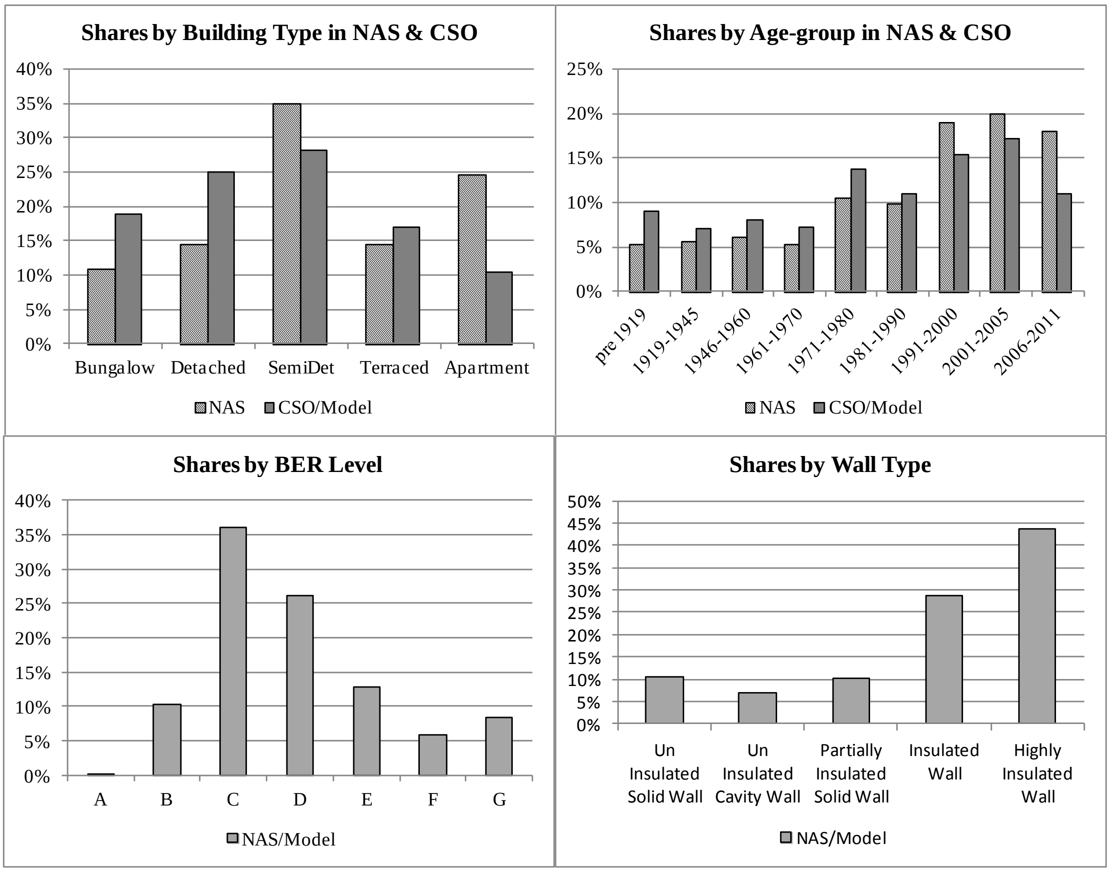

Figure 3.4: *Shares of dwellings by Building Type, Age Group, BER and Wall Type in both the NAS and CSO databases.*

3.5 Numbers of dwellings retrofitted by archetype.

3.5.1 Which archetype dwellings to retrofit?

The numbers of dwellings to be retrofit will be specified on a scenario by scenario basis, for example taking national policy targets as inputs or using exploratory scenario assumptions. For a given number of dwellings to be retrofitted, it is necessary to decide which, if any, archetype dwellings are more likely to be retrofitted than the others. To examine this we first look for analysis on the determinants of which dwellings have undertaken retrofit measures in the past.

Research by SEAI[88] examining participation in the HESS concludes that participants come from a wide cross section of society. Participants incomes are shown to be representative of national patterns although the vast majority of investments are funded by savings rather than borrowing. Retired householders were more likely to avail of the grant than younger adults and detached dwellings were more likely to be retrofitted than apartments or semi-detached dwellings, reflecting a number of underlying factors such as ownership patterns and differing construction techniques across different building types. Data on the BER of dwellings prior to undergoing retrofit or on the age band of the dwelling was not available. Using BER bands or age groups to weight the retrofitting of dwellings to particular archetypes would intuitively have seemed a plausible option, as it would be assumed that older dwellings or dwellings with a poorer BER would be more likely to undergo retrofit. However there is insufficient evidence to link the likelihood of a dwelling undergoing retrofit to either of these dwelling characteristics. Instead the most definite trend associated with the uptake of retrofit measures was the tendency for householders to focus on cheaper, less intrusive, "shallow" retrofit measures, rather than more expensive "deeper" measures. This can be seen from Table 3.5 which shows the breakdown of measures applied for and completed under HESS along with the level of grant support provided, based on data given in [88]. Of the three types of wall insulation it can be seen that cavity wall is significantly cheaper than internal or external wall insulation. Cavity wall insulation is only suitable for use on UICW dwellings while external/internal wall insulation can be used on any wall type and are typically used for retrofitting UISW and PISW dwellings. The average spend under the HESS, including grant was just €2,900 resulting in a large uptake of shallow measures, such as roof and cavity wall insulation and a low uptake of more expensive measures such as external wall insulation. On this basis wall construction type has thus far been a good predictor of whether a dwelling will undergo retrofit, with UICW dwellings more likely to undergo retrofit than UISW or PISW dwellings. For this reason we choose to use wall type as the factor on which to weight dwelling archetypes as being more or less likely to undergo retrofit or become obsolete, rather than the age or the BER of the dwelling.

This is a significant point differentiating this model from other bottom up models of Ireland's residential sector. We believe wall construction type is an important variable in this analysis and our use of the NAS database for this purpose has not been done previously. Where estimates of the availability of UICW for retrofit have been made they have mostly been based on anecdotal evidence regarding building practices in particular parts of the country during various time periods. Ahern et al made use of the NSHQ for this purpose but the authors do not consider this dataset to be sufficient to properly address this issue due to the significant uncertainty amongst respondents regarding the wall construction type of their dwellings. We note that it is still possible to use BER or age group as a weighting factor if data becomes available linking these factors to retrofit rates or obsolescence, or if for particular regions data on wall construction type is unavailable. The actual weighting factor applied to each archetype then needs to be estimated for both retrofitting and obsolescence. These weightings can vary on a scenario by scenario basis.

HESS Measures	Grant €	Approximate Cost €	% of participants applied for	% of participants completed
Roof Insulation	200		84	70
Cavity Wall Insulation	320	1,200	61	53
Heating Controls Upgrade	400		7	4
High Efficiency Gas Boiler & Heating Controls Upgrade	560	2,800	19	15
High Efficiency Oil Boiler & Heating Controls Upgrade	560	2,800	17	10
Internal Wall Dry-Lining	2,000	9,000	8	4
External wall insulation	4,000	20,000	4	2

Table 3.5: *Applications and uptake of measures in HESS*[5]

3.5.2 Obsolescence

The rate at which dwellings in the Irish housing stock become obsolete is not well understood but has been estimated by the Department of the Environment to be 0.73% of the total housing stock per annum[86]. International estimates of obsolescence are lower and vary from 0.1% to 0.4%[68] but previous estimates of the Irish rate by the ESRI have varied from 0.4% to 1%[90]. In this paper we have chosen to take the Department of the Environment value of 0.73%. The total number of dwellings in the housing stock from 2011 to 2020 is taken from projections by the ESRI. 0.73% of this total figure is subtracted annually from the number of dwellings existing as of 2008, assuming that no dwellings constructed after 2011 will become obsolete within the time frame.

3.6 Energy savings potential for a range of retrofit measures.

3.6.1 Overview

To calculate the energy saved for a given retrofit measure carried out on a given archetype dwelling we use the DEAP building physics model developed by SEAI for the calculation of BERs. DEAP

[5] Figures for approximate cost of measures taken from 1. Curtin, J., *Greenprint; For a National Energy Efficiency Retrofit Programme*. 2009.

requires as inputs a detailed description of the physical characteristics of the dwelling. To provide these values we devise an average dwelling for each archetype category based on the data within the NAS database. This gives us a baseline energy consumption. The technical potential for savings generated through retrofit measures is then modelled by adjusting the appropriate dwelling characteristics, e.g. improving the wall U value in the case of adding external wall insulation, and re-running DEAP. The development of the average dwellings and the subsequent DEAP analysis are presented in the follow sections.

3.6.2 DEAP energy calculations

A detailed description of the inputs and outputs for the DEAP modelling procedure can be found on the SEAI website[41]. A full list of the data taken from the NAS database for input into DEAP is provided in Appendix B. A brief description of some of the inputs under the different calculation modules within DEAP is given below:

- Dimensions: Takes as inputs the floor area, room height and living area fraction.
- Ventilation: Takes as inputs the numbers of openings (chimneys, flues etc), structural air tightness and ventilation method.
- Building Elements: Takes as inputs the area and U-value of floors, roofs, walls, doors and windows.
- Water Heating: Takes as inputs whether or not there are distribution or storage losses, the volume of hot water tank, the level of insulation on tank and pipes.
- Distribution System Losses and Gains: Takes as inputs data on the heating system controls and responsiveness.
- Energy Requirements: Takes as inputs the efficiency of space and water heating systems, fuel type and presence of renewable energy technologies.

DEAP assumes set internal temperatures and heating profile. Daily hot water demand is automatically calculated based on standard assumptions on litres per occupant, with the number of occupants being itself automatically calculated as a function of the floor area. An internal gains section calculates the net internal heat gains due to lighting, the water heating system, metabolic gains, appliances & cooking and the heat loss to the cold water network. The figures for metabolic gains, appliances & cooking and losses to the cold water network are based on standard calculations taking into account floor area and number of occupants. DEAP calculates both delivered and primary energy requirements, but it is the primary energy requirement that is used for BER grades and is also used for this model. The primary energy conversion factors for different fuel types are provided in Table 8 of the DEAP manual[48].

3.6.3 Development of average archetype values

To provide the large amount of input data required to model each archetype dwelling in DEAP we again make use of the NAS database. Using the archetype classifications developed earlier, we first split the 253,875 NAS dwelling entries, post filtering, into each of the archetype dwelling categories. Naturally some archetype categories contained more NAS entries than others, some of the notional categories contained no dwellings, for example there were no dwellings with UISW achieving an A BER rating. Archetypes with less than 10 dwellings were also ignored. Furthermore based on the assumptions outlined in the previous section that no dwellings in the HIW category would either become obsolete or be retrofitted in the timeframe considered those archetypes were not analysed . Therefore of the 175 original archetypes 112 were used for the model calculations.

3.6.4 Individual retrofit measures

We examined 6 retrofit measures, based closely on the measures supported in the past by the HESS and currently under BEH, with the inclusion of window insulation, a common retrofit measure external to any government support scheme. The six measures were roof insulation, cavity wall insulation, solid wall insulation, boiler and heating controls upgrade, solar hot water and high performance windows. We considered that this list covered the range of retrofit options most likely to be undertaken on existing dwellings. Other possible fabric improvements such as floor insulation were considered unlikely to be widely undertaken. A brief description of each retrofit measure is given below, while Figure 3.5 shows a sample of the U value and efficiency improvement profiles, using C and F BER grade dwellings from different wall construction archetypes as examples.

- Roof Insulation: We assumed that dwellings retrofitted with high specification roof insulation would achieve a roof U value of 0.13. It was assumed that it was possible to carry out roof insulation on all archetypes with the exception of apartments. The apartment archetypes included bottom and mid floor apartments which have no roof heat loss, therefore it was decided that roof insulation did not make sense in this context and would not be applied to apartments.
- Cavity Wall Insulation: We assumed that dwellings with cavity wall insulation would achieve a wall U value of 0.33. Only UICW archetypes can avail of this option.
- Solid Wall Insulation: We use the term solid wall insulation to account for either external or internal wall insulation retrofit. These two technologies are grouped because they are applicable to the same archetype categories, i.e. dwellings for which cavity wall insulation is not suitable, and they can achieve similar final U-values. There are advantages and disadvantages with either option with regard to cost, ease of insulation, disruption during installation etc and the final choice for a given dwelling as to whether to install external or internal wall insulation is likely to come down to the unique properties of the individual dwelling and the occupants. We assume that dwellings retrofitted with solid wall insulation would achieve a wall U value of 0.27. It can also be applied to PISW and IW archetypes.
- High Performance Windows: Retrofitting of dwellings with high performance windows was modelled by changing the window U value and solar transmittance values , also known as the solar factor or g-value. It was assumed that high performance windows could be installed in any dwelling with an existing window U value of less than 2.0 and that the U value after retrofit would be 1.3. The solar transmittance was assumed as 0.4. These assumptions are based on a review of the National Standard Authority of Ireland (NSAI) window energy performance certification scheme and correspond approximately to an A3 certified window[91].
- High Efficiency Boiler and Heating Controls Upgrade: Retrofitting of dwellings with high efficiency oil and gas boilers is modelled by changing the space and water main system efficiency fields and improved heating control systems are modelled by changing the space and water efficiency adjustment factors. Post retrofit it is assumed that boiler efficiency is 92% and the efficiency adjustment factor was 1 corresponding to a condensing boiler with thermal store, as per table 4c of the DEAP manual [48]. It was assumed that boiler efficiency upgrades could be

carried out on any dwelling with an existing boiler efficiency less than 92%. The main incidence of dwellings with existing boiler efficiencies great than this was for dwellings with electric heating, which is given an efficiency of 100% in DEAP and which were therefore not considered for retrofitting. This was mostly the case for apartments.

- Solar Hot Water: Modelling the installation of solar hot water requires as inputs data on the solar fraction and the solar storage volume. The solar fraction is a figure indicating the proportion of the solar hot water yield relative to the total dwelling hot water demand and is set at 60%, in line with best practice guidelines set out in DEAP, as a solar hot water system with a solar fraction of greater than 60% is considered to be over sized. The solar storage volume is assumed to be half of the total hot water storage volume, which is a typical design figure. It was also assumed that the solar water pump was not photo-voltaic powered

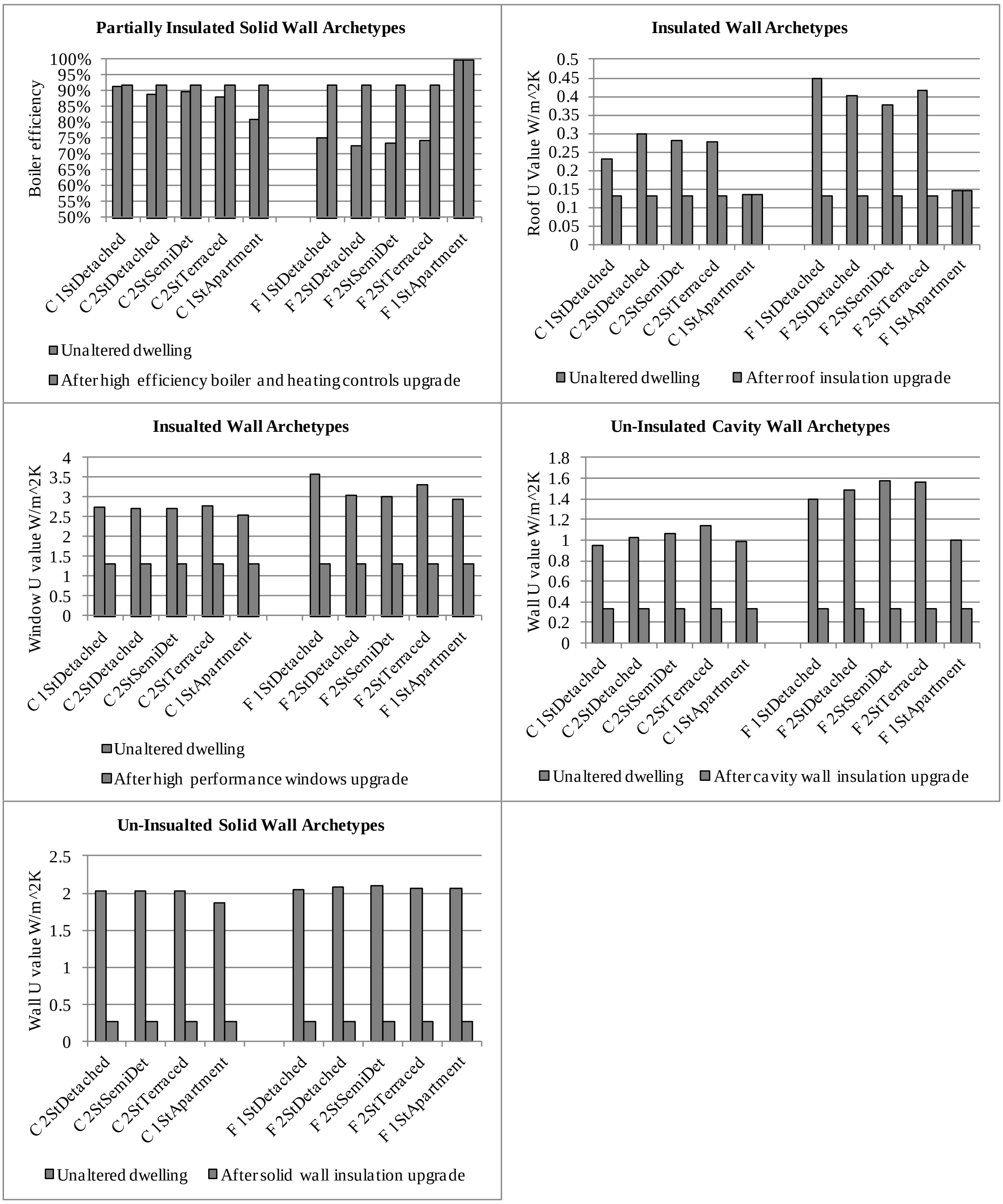

Figure 3.5: *Retrofit improvement profiles*

3.7 Differences in predicted and actual energy usage & energy savings

The technical energy savings potential of a given measure on a particular dwelling as calculated by a deterministic heat flow model such as is used in this analysis is unlikely to be fully realised due to a number of potential factors which can be grouped under two headings, pre-bound and rebound.

3.7.1 Pre-bound

The term pre-bound has been coined by Sunikka-Blanka and Galvin [92] to account for the differences observed between the annual dwelling energy consumption as calculated by deterministic heat flow models (such as those used to produce Energy Performance Certificates and the one used in this model) and the actual observed or metered annual energy consumption of real world dwellings. There are a number of possible causes for this discrepancy.

Firstly the data input by the user or energy modeller on the physical characteristics of the dwelling may not be accurate, even if collected through onsite inspection. For example U-values of elements such as walls are generally not measured in situ, but rather assumed from tables of default values, often within software packages, based on the observed construction method. A recent study finds that in many cases this overestimates the U-value and recommends further research [93]. Other sources of error in the input data may include poor workmanship or non compliance with building regulations resulting in actual U-Values being higher than the assumed defaults, boilers working at less than optimal efficiency due to poor maintenance, assessor errors etc. Secondly, as well as the user input data on the physical characteristics of the dwelling, standardised energy performance calculations typically require assumptions to be made on key operating variables such as internal temperature, hours of heating and air changes required, which are heavily dependent on the behaviour of the occupants. As no particular household is likely to exactly match these assumed behavioural patterns this will result in inaccurate calculation of energy demand. Thirdly, for a given set of input data and assumptions, the algorithms used to calculate the energy consumption are necessarily a simplification of reality and will not correspond exactly to real world energy consumption.

Studies across the EU have found that different energy performance calculations in a number of different countries systematically over estimate the annual energy consumption of dwellings, particularly for less efficient dwellings[92].

3.7.2 Rebound

Whereas the “pre-bound” effect is simply a collective term for a number of model inaccuracies that lead to a difference between predicted and actual energy consumption in the base case, the rebound effect refers to the situation whereby a number of the key operating variables determining energy consumption change as a direct result of the increased efficiency of the building and have a counteracting effect. A key factor is the increased ease and affordability of heating a dwelling with greater energy efficiency, which leads occupants to increase the internal temperature, heating hours or proportion of the dwelling that is heated, and results in a portion of the efficiency gains being realised as increased service demand and comfort levels, rather than as a decrease in energy consumption. The increase in observed comfort levels is not necessarily entirely down to occupant preference, as dwellings with increased energy efficiency will inherently retain heat better and have higher internal temperatures during unheated periods, which leads to an overall increase in average internal temperatures even when there is no increase in the desired living area temperature during heating periods. Typically, engineering estimates of the energy savings potential of a retrofit measure assume no change in many of these operating variables before and after retrofit, and so overestimate the energy savings potential.

The savings presented in the following results section represent the maximum technical energy savings for the given measures and do not account for rebound effects. The authors do however investigate the potential scale of rebound effects for particular dwelling types, without explicitly commenting on the likely degree that would be observed across the entire stock of retrofitted dwellings, which would require an economic analysis that is outside the scope of the current work.

3.8 Results

Here we present a sample of typical results obtained for the technical energy savings potential of particular retrofit measures on particular dwelling types. The model considered 175 archetypes, 112 of which were available for retrofitting, with 5 retrofit measures performed on each giving 560 theoretical energy savings results.

Results can be displayed in terms of either delivered or primary energy. The delivered energy demand accounts for the efficiency of energy conversion technologies on site, e.g. boilers, but not off site, e.g. electricity production, gas network transmission losses etc. The conversion factors from delivered to primary energy are given in Table 8 of the DEAP manual [48]. When estimating the reduction in metered energy consumption for an individual dwelling, for example the reduction in an electricity bill, delivered energy is used whereas when considering the amount of energy savings that can contribute to EU energy efficiency and CO2 targets, primary energy is used. Significantly, electricity is given a conversion factor of 2.7, reflecting the historical inefficiency of the electricity grid. This can result in energy savings for a given measure on an archetype with electric heating to be significantly greater than might otherwise be expected.

Figure 3.6 shows sample results, in primary energy, for each retrofit measure and a selection of building types. C and F BER ratings are chosen to show the trends across the energy performance spectrum. As discussed in section 3.6.3 for measures other than wall insulation the savings for the UICW and PISW archetypes are the same, and cavity wall insulation can only be installed in UICW dwellings. In broad terms, dwellings with poorer initial BERs have greater technical savings potential as should be expected. There are many variables determining the energy consumption of every archetype, so there is not a simple linear relationship between the savings achieved for a particular measure on different archetypes. For instance if after the installation of wall insulation two different archetypes both experienced the same improvement in wall U-value, differences in floor area, share of space heating energy consumption, heating efficiency etc would result in different kWh/m2/annum energy savings in each. In this sense the results are highly archetype specific and it is not possible to extrapolate from one to another. Figure 3.7 provides a comparison of primary and delivered energy savings for sample measures and archetypes. Where there is a significant difference between the delivered energy and primary energy savings, this is as a result of electricity being used.

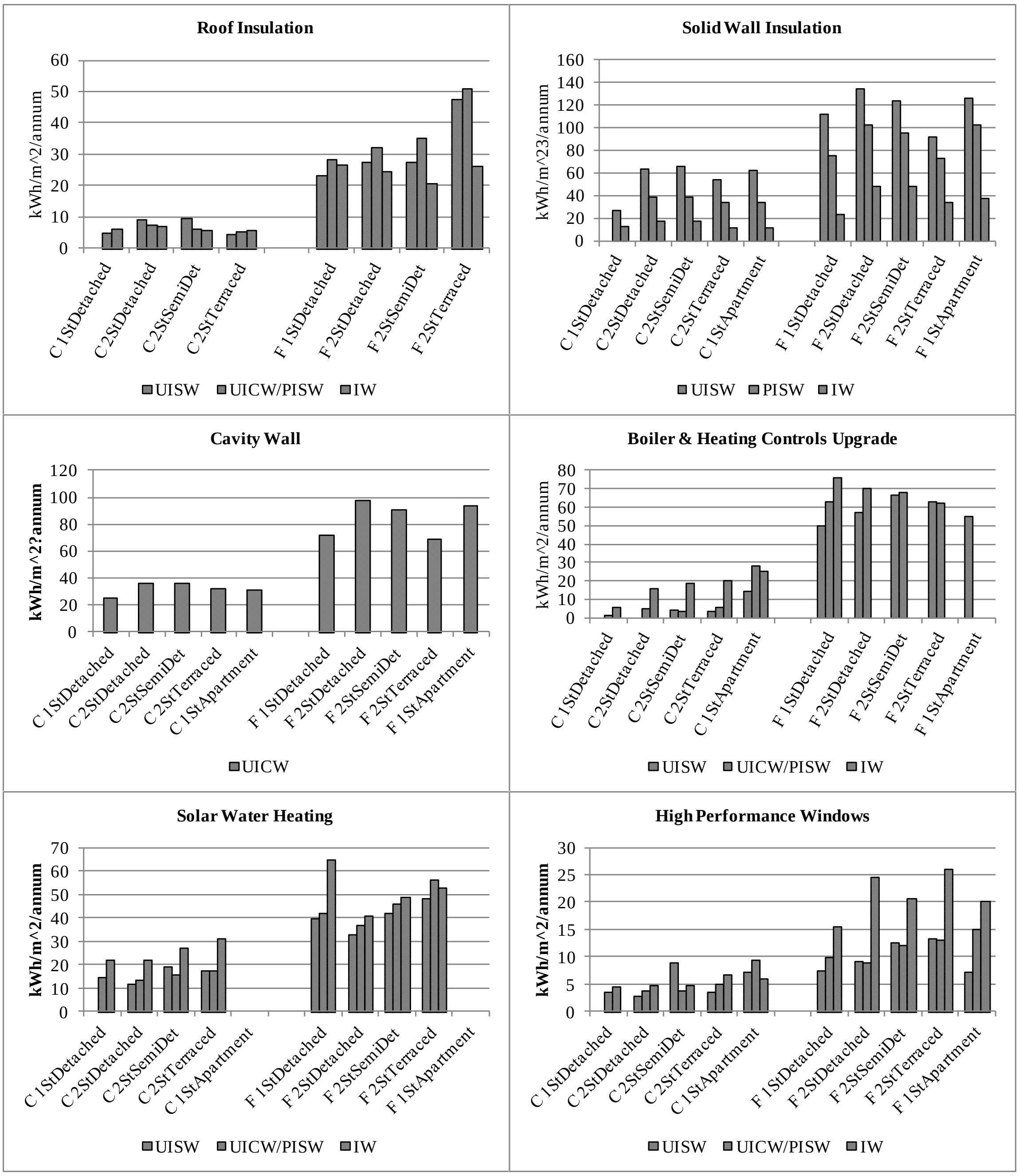

Figure 3.6: *Primary Energy Savings after the application of particular retrofit measures on sample dwellings.*

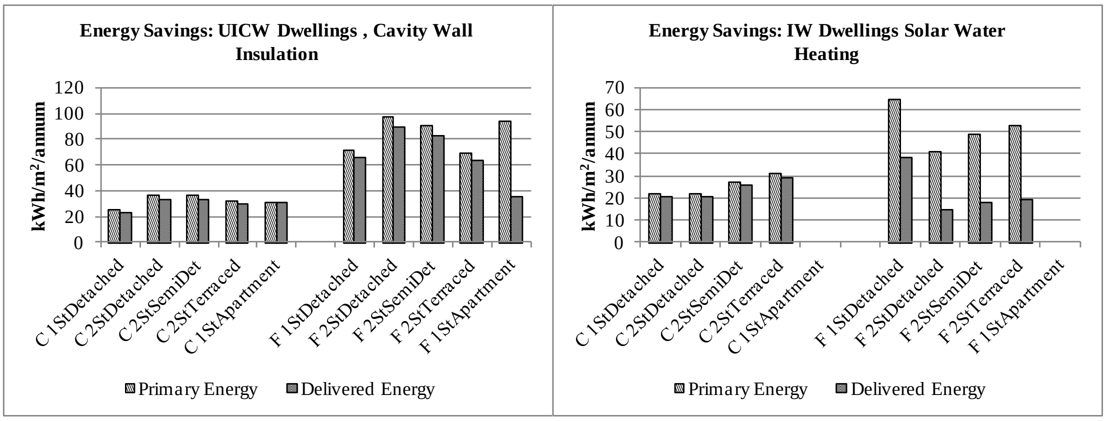

Figure 3.7: Comparison of delivered energy and primary energy savings for sample measures and dwelling archetypes.

3.9 Discussion

The examples shown demonstrate the variation in the results across different dwelling types. The level of variation in the energy savings potential of particular retrofit measures between different dwelling types, not even accounting for the complexities added by rebound and behavioural effects, presents a difficulty in producing a cost benefit analysis of particular retrofit measures. It also highlights issues with a simple grant structure that offers the same level of financial support for a given measure regardless of the technical energy savings potential of implementing it on a given dwelling. It had originally been suggested that BEH and future grant schemes would move toward a system where the level of grant aid was linked to the technical energy savings potential of that measure on the particular dwelling in question through the use of before and after DEAP calculations, though this approach has not yet been implemented and may be superseded entirely by proposals to end direct exchequer funding in the form of grants and shift instead to a more market-based approach to promoting residential retrofit.

The high level of disaggregation of results is a benefit of the bottom up method. Aggregating or averaging the results is possible, for instance to give the average energy savings for a given retrofit measure, but much of the detail is lost in the process. Rather than simple averaging a more detailed scenario based analysis is a far more useful approach. The scenarios should be constructed in order to investigate the upper and lower bounds of what energy savings are likely to be achieved for given targets, policies or degrees of investment. Note that for scenario analysis involving the application of multiple retrofit measures it is necessary to re-run the model for combinations of measures rather than simply summing the savings from individual measures. The DEAP calculation uses an intermittent heating profile which means that even for independent retrofit measures such as roof insulation and wall insulation, the savings are not additive, that is the modelled savings after implementing both measures are not equal to the sum of the savings from the measures implemented individually. This scenario analysis forms part of further work by the authors that falls outside the scope of this methodological paper.

As can be seen from Figure 3.6, cavity wall insulation can achieve the same scale of savings as more expensive solid wall insulation at a fraction of the cost. There is a strong willingness amongst householders to invest in cavity wall insulation but not, so far, in solid external/internal wall insulation. This is an important consideration for scenario analysis. It is necessary to have an accurate assessment of the potential for further take up of cavity wall insulation. The success of current mechanisms in leveraging funds for shallow measures will sharply diminish as the number of cavity wall dwellings left to be retrofitted approaches exhaustion. At that point energy efficiency improvements will stall unless policy is in place to ramp up the uptake of deeper measures. This fact has been recognised by the relevant Irish authorities but the challenge remains to enact policies that can leverage the significant investment required to retrofit large numbers of solid wall dwellings.

3.9.1 Sensitivity of results to internal temperature assumptions

DEAP uses a set of standard internal temperature assumptions for the purpose of producing BERs. The BER is an asset rating and is used to compare different dwellings thus the same internal temperature assumptions are used for all dwellings to ensure a fair comparison. DEAP assumes two temperature zones in each dwelling, the living area and non-living area. The fraction of floor area that is living area is a dwelling specific variable. Standard assumptions are for a living area temperature of 21degC and a non living area temperature of 18degC. The living area fraction is used to calculate the average internal temperature across the whole dwelling and this is used for heat loss calculations. The standard heating profile used is of 2 unheated periods of 8 hours duration each day. No differentiation is used between weekdays and weekends. It is assumed that during heating periods the standard internal temperatures are constantly achieved. The final heat loss calculation is based on a monthly adjusted internal temperature, calculated based on the monthly mean external temperature, the mean internal temperature required during heating periods and an intermittency temperature factor which accounts for the rate of heat loss during unheated periods. The latter is calculated based on the internal heat capacity of the dwelling which is specified in one of 5 bands for each dwelling.

The set internal temperatures during heating hours correspond to those recommended by UK government as providing adequate thermal comfort and avoidance of issues related to cold strain, though the World Health Organisation and other studies, including Healy et al, have used 18deg C as a benchmark comfortable living room[72]. As such they are likely to give a good estimate for dwellings where it is economical for the occupants to achieve these values. This is more likely to be the case for newer dwellings and those with good BER results. It is not likely to give a good estimate for dwellings with poorer BER results, especially so for those at the very end of the spectrum, which would be highly uneconomical to heat to these ideal conditions and in practice are likely to have lower indoor temperatures for the sake of lower fuel costs resulting in lower fuel consumption. The standard internal temperature assumptions are, therefore, likely to overestimate the energy consumption of these dwellings in the base case.

We investigate the sensitivity of the results to this factor by running a modified DEAP calculation with varying internal temperatures. For an indication of the range of internal temperatures likely we consider the results of research by Healy and Clinch into thermal comfort and fuel poverty in Ireland in 2001 [72]. They define households experiencing fuel poverty as those surveyed who declare that they have an inability to heat their home to a comfortable level. Table 3.6 is drawn from their research and shows living room temperatures recorded across a range of 1500 households surveyed in March 2001. The temperatures were recorded on a once off basis during face to face interviews in the living room of the dwelling. Healy and Clinch acknowledge the shortcomings of such an approach noting that, for example, households may heat the room to a higher level than that to which it is normally heated in anticipation of the interview and that a warm living room can be found in an otherwise cold house [72]. Despite these limitations the survey still provides a useful indication of the broad range of temperatures which ought to be considered in the type of sensitivity analysis in question. We test 4 internal temperature scenarios based on the mid points of the 4 temperature ranges from Healy and

Clinch with the greatest number of dwellings, as shown in Table 3.7. We modified the DEAP calculation with these revised internal temperatures and re-ran the model. Sample results for PISW dwellings of C and F BERs are shown in Figure 3.8. For PISW dwellings primary energy consumption was reduced on average by 30% relative to the standard DEAP assumption in the low temperature scenario, 15% in the mid temperature scenario and increased by 16% in the high temperature scenario, or approximately a 15% change in energy consumption for every 2 degC internal temperature shift. It should be noted that the average fuel poor dwelling living room temperature is less than 1 degC less than the average non fuel poor temperature, according to Table 3.6. For dwellings where over heating through inefficient heating patterns is an issue this highlights the efficiency gains to be achieved through modest reduction in internal temperature, but conversely also highlights the potential in fuel poor dwellings for even large efficiency gains to be realised only as increased internal temperature.

Living room temperature degC	Fuel poor households	Non fuel poor households
<16	6%	2%
16-17.9	24%	9%
18-19.9	39%	39%
20-21.9	19%	33%
22-23.9	9%	11%
24-25.9	3%	6%
Average	19.21 degC	20.19 degC

Table 3.6: *Living room temperatures recorded in fuel poor and non fuel poor households.*

Scenario	Living area temperature degC	Non living area temperature degC
Low Temp	17	14
Mid Temp	19	16
Standard DEAP	21	18
High Temp	23	20

Table 3.7: *Temperature sensitivity analysis assumptions*

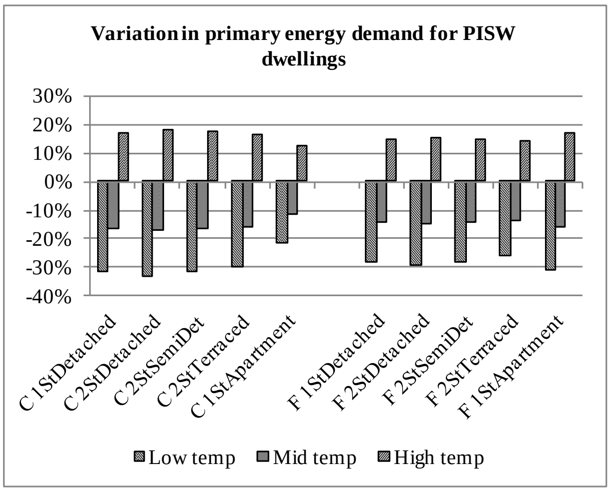

Figure 3.8: *Variation in Primary Energy Demand of PISW dwellings under different internal temperature scenarios, with respect to the standard DEAP assumptions.*

3.9.2 Potential rebound effect on technical savings potential

Varying the internal temperature for energy demand calculations before and after retrofit allows us to investigate the potential scale of the rebound effect post retrofit measures, as the rebound effect for residential retrofit is primarily through households increasing internal temperature and heating periods post retrofit. As discussed previously a thorough analysis of likely rebound effects is outside the scope of this paper and is left for further work, but some initial analysis presented here shows the potential magnitude of the effects for individual dwellings. For example we can examine the difference in energy consumption for a dwelling that has low internal temperatures pre retrofit, potentially experiencing fuel poverty, and which post retrofit increases internal temperature to standard DEAP levels. We define percent rebound as:

$$R = \frac{E_s - E_R}{E_s} \times 100$$

E_S = Energy savings due to retrofit measures with standard DEAP internal temperature before and after retrofit

E_R = Energy savings due to retrofit measures with increased internal temperature after retrofit.

Figure 3.9 and Figure 3.10 show the percentage rebound for two retrofit scenarios for a sample of PISW dwellings. As was the case for energy savings, the level of rebound for a given internal temperature increase is determined by many variables for each archetype, including floor area and the efficiency of the heating system, but some general trends are seen. The absolute rebound effect in kWh/m^2/annum is greater for less efficient dwellings relative to more efficient dwellings, for example for C BER dwellings in comparison to F BER dwellings. The rebound expressed as a percentage of the retrofit savings is larger in the more efficient dwellings as the retrofit savings for these dwellings are smaller. Similarly the rebound when expressed as a percentage of the retrofit savings for a deeper set of retrofit measures, as in Figure 3.10, will be smaller than for shallower measures, due to the larger denominator.

Although rebounds greater than 100% are shown here in reality this is unlikely to be the case as it would imply that a household chooses to increase its expenditure on energy post retrofit. Rather the worst case scenario is likely to be that a household simply keeps their energy expenditure constant and realises 100% of the efficiency gains through increased comfort levels rather than decreased energy consumption. What this may indicate is that even post retrofit it will be uneconomical for this household to adequately heat their dwelling, and even if further retrofit measures are implemented further efficiency gains will continue to be realised as improvements in comfort before any reduction in energy consumption is observed. As discussed in 3.9.1 the temperature increase from the low temperature to standard DEAP scenarios is 4 degrees which would be a considerable increase in temperature and it is not known in what proportion of dwellings this would actually be realised. We do not suggest that the rebound levels shown in Figure 3.9 should be applied generally to these archetypes. This scope for rebound effect will reduce the effectiveness of residential retrofit as an energy efficiency and green house gas abatement strategy but as noted by Healy and Clinch this does not reduce the economic value of residential retrofit measures to society as a whole as the increased thermal comfort realised instead of energy reduction is at least as valuable to the occupants as the cost of the energy that would otherwise be saved and has significant benefits to society in terms of reduced morbidity and mortality.

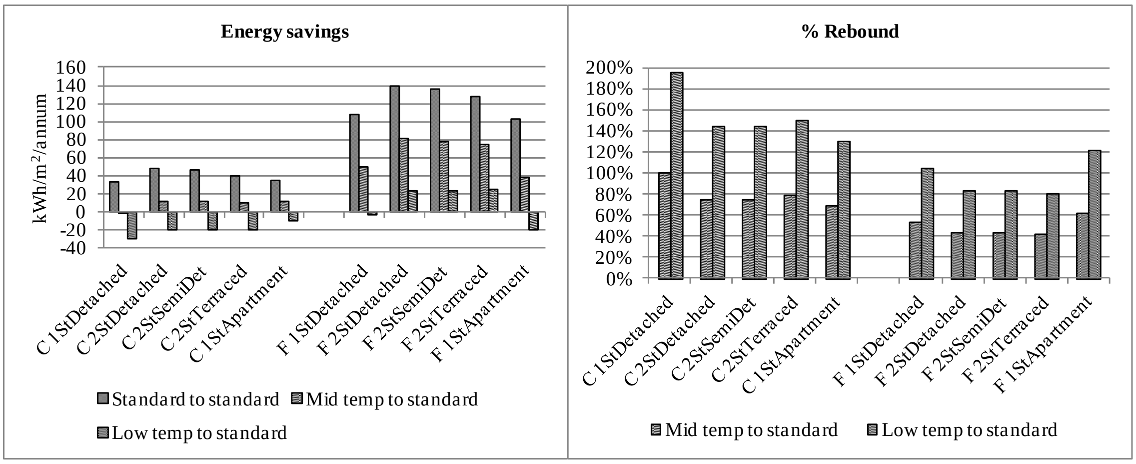

Figure 3.9: *Energy savings and % rebound, post retrofit of roof and solid wall insulation in PISW dwellings, for different pre and post retrofit internal temperature assumptions.*

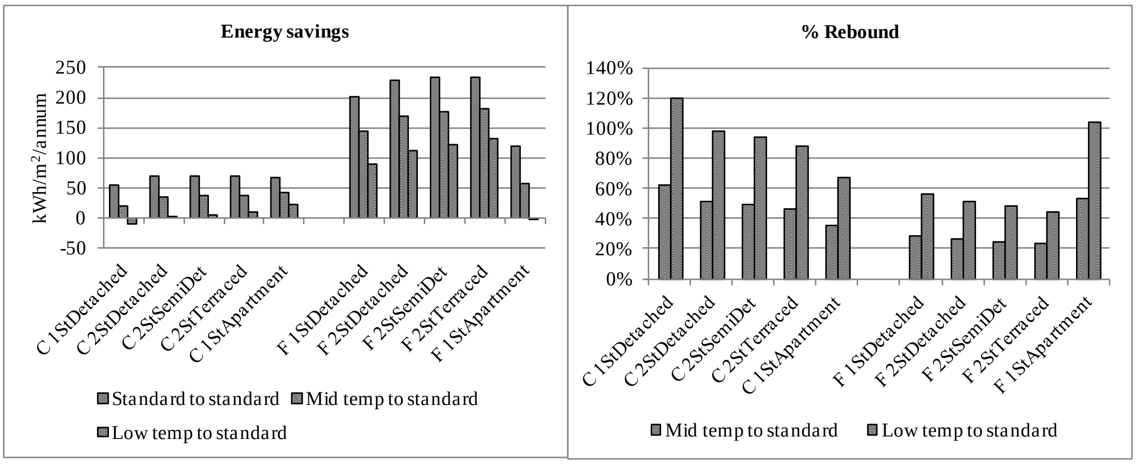

Figure 3.10: *Energy savings and % rebound, post retrofit of roof & solid wall insulation, boiler & heating controls upgrade, solar hot water & high efficiency windows in PISW dwellings, for different pre and post retrofit internal temperature assumptions.*

3.10 Conclusions

This paper presents a bottom up approach to modelling the energy demand from the space and water heating end uses of the 2011 stock of residential dwellings and a method for estimating the energy savings potential of various building fabric retrofit measures in the future. It takes advantage of the NAS BER database, a newly available and rich dataset on the construction characteristics of the housing stock in Ireland. This data enables analysis based on wall construction type. The wall construction type of a dwelling is an important consideration in terms of what retrofit measures are possible to implement and what improvement in energy performance is possible. For this reason we choose to use wall type as the factor on which to weight dwelling archetypes as being more or less likely to undergo retrofit or become obsolete, rather than the age or the BER of the dwelling. The results presented at this stage are a sample of the highly disaggregated outputs that can be generated using the bottom up methodology adopted. These results can in turn be used as inputs for scenario analysis to determine the upper and lower bounds of what energy savings are likely to be achieved for given targets, policies or degrees of investment. We investigate the sensitivity of the model to assumptions regarding the internal temperature and find that the there is a large scope for rebound in fuel poor dwellings which will reduce the effectiveness of residential retrofit as an energy efficiency and green house gas abatement strategy but which should not reduce the benefit of residential retrofit measure to society as a whole. We also note that much further work remains to be done in this area.

Chapter 4

4 One energy efficiency programme but a range of possible energy savings.

Abstract

This paper estimates the potential energy savings that may be achieved in the Irish residential sector by 2020 due to the introduction of an ambitious retrofit programme. We estimate the technical energy savings potential of retrofit measures targeting energy efficiency of the space and water heating end uses of the 2011 stock of residential dwellings between 2012 and 2020, using a bottom up model described in previous work by the authors. In order to investigate the range of energy savings possible we build eight separate scenarios varying the number of dwellings retrofitted and the depth of retrofit carried out. In 2020 the estimated savings potential lies in the range from 1,713 GWh to 10,817 GWh. but is more likely to fall within the lower end of this range, i.e. between 2,000 and 4,000 GWh. This compares with target savings of 5,200 GWh. These theoretical savings do not take into account the reduction in realised savings due to direct or indirect rebound effects. We conclude that this target is technically feasible but very challenging and unlikely to be achieved based on progress to date. It will require that 750,000 dwellings be retrofitted and a significant shift towards deeper retrofit measures.

Keywords: Residential, Retrofit, Policy

4.1 Introduction

This paper estimates the technical energy savings potential in the Irish residential sector due to the introduction of an ambitious national residential energy efficiency retrofit programme. We use a bottom up model of the existing housing stock described in previous work by the authors, and which also builds on previous bottom up modelling of residential sector energy consumption.[25, 62, 63]. To investigate the range of energy savings possible we build eight separate retrofitting scenarios varying the number of dwellings retrofitted and the depth of retrofit work carried out. A bottom-up engineering archetype model of the Irish residential sector is used to estimate the technical savings potential of the retrofit scheme. As such it can be considered that this work presents an upper bound on the savings potential under each of the scenarios considered.

The layout of this paper is as follows: Section 4.2 provides the policy context for modelling residential retrofit measures in Ireland. Section 4.3 gives an overview of the modelling methodology used. Section 4.4 develops a number of scenarios to investigate the potential for energy savings due to a national building retrofit programme. Section 4.5 presents the results obtained and section 4.6 discusses. Section 4.7 draws conclusions and discusses the limitations of the approach taken, pointing to further research areas and work to be done.

4.2 Policy context

Retrofitting of building fabric has been identified as one of the most effective and cost efficient ways to achieve energy savings in the economy, with the potential for savings in developed countries estimated to be in the range of 60% to 80% of energy use [94, 95], and generally achievable at negative cost in green house gas (GHG) marginal abatement cost curves, i.e. yielding a net saving over the time frame considered [96-98]. The International Energy Agency has repeatedly identified increased end-use energy efficiency as the quickest, least costly method of GHG mitigation, most recently in the 2012 World Energy Outlook [99]. Energy efficiency at the EU level is promoted through the Energy Efficiency Directive (EED) [100], which supersedes the Energy Services Directive (ESD) [28] and, for the built environment in particular, through the recast Energy Performance in Buildings Directive (EPBD) [42, 101]. Acknowledging this scope for cost effective energy efficiency gains the EPBD requires all member states to improve the minimum energy performance requirements for new building and existing buildings undergoing renovation to a cost-optimal level.

In response to the requirements of the ESD, Ireland submitted its first National Energy Efficiency Action Plan (NEEAP1) in June 2007 [28, 33]. It specifies an overall energy savings target of 32,000 GWh across the whole economy to be achieved in 2020. At the time of publication of NEEAP1 24,000 GWh of savings had been accounted for by specific measures, 10,355 GWh of these from the residential sector, with a further 8,195 GWh remaining to be realised by additional measures[33]. The second plan (NEEAP2) is to be submitted in June 2013 [102]. The NEEAP2 should include analysis and evaluation of the NEEAP1, as well as updated plans and details of new measures to address any existing or projected shortfalls.

The ESD also requires the provision of dwelling energy performance certificates. In Ireland these are known as Building Energy Rating (BER) certificates and are managed by the Sustainable Energy Authority of Ireland (SEAI). The BER provides an asset rating of the technical energy performance of domestic dwellings, assigning each a rating from A1-G based on a calculation of primary energy consumption in kWh/m^2/annum. The BER calculation is carried out using the Dwelling Energy Assessment Procedure (DEAP). The DEAP software tool requires as inputs a detailed description of the building envelope and heating system. It takes account of space heating, water heating, ventilation and lighting calculated on the basis of standard assumptions on occupancy, heating patterns, internal temperature etc. The results of every BER carried out as well, as the large amount of data collected on the physical characteristics of each dwelling required for the associated DEAP calculation, are stored by SEAI in what is known as the National Administration System (NAS) database. By mid 2012 this NAS BER database contained details of approx 300,000 dwellings, out of a total dwelling stock of 1.6 million. This BER data has been made publicly available for research purposes through the SEAI website.

4.2.1 Residential energy efficiency retrofitting schemes in Ireland

SEAI in conjunction with the Department of Communications Energy and Natural Resources (DCENR) has run a number of schemes aimed at encouraging energy efficiency retrofit works for existing dwellings in the Irish residential sector. Past examples include the Home Energy Savings Scheme (HESS) and the Warmer Homes Scheme (WHS). Each of these schemes provided a financial incentive to home owners to undertake energy efficiency retrofit measures through the mechanism of direct subsidy for specific measures carried out. More than 83,000[6] homes availed of the HESS scheme between 2009 and the end of 2011 to install improved insulation, high efficiency boilers and heating controls while over 82,000 low income households have been upgraded through the Warmer Homes Scheme which focused on alleviating fuel poverty, providing increased thermal comfort and associated health benefits, as well as energy savings [103]. Evaluations of these two programmes have found substantial net benefits for society and significantly reduced energy bills for householders[104].

During 2011 the "Better Energy: The National Upgrade Programme"(BE) scheme was introduced, which superseded all previous energy retrofit programmes, both residential and non-residential, and which set the objective of delivering energy efficiency upgrades to one million residential, public and commercial buildings by 2020. As such it is potentially the most ambitious energy-related initiative ever introduced in Ireland. As well as being a core plank of Ireland's energy and environmental policies, its importance as a source of potential employment and investment in the hard hit construction sector, so called "green jobs", has also been widely emphasised[6, 89, 105]. All previous residential retrofit schemes were superseded by the residential branch of the programme, "Better Energy: Homes" (BEH). 75% of the overall programme funding will go to BEH, of which 40% will go to addressing energy poverty. The remaining 25% of total funds will be made available for efficiency measures in the non-residential sector, evenly split between energy efficiency measures in the public sector and measures in the business and voluntary sector[106]. The target of 1 million building retrofits, the vast majority of which are expected to be residential, is highly ambitious considering the current dwelling stock contains approximately 1.6 million permanently occupied dwellings, and that a significant proportion (28%) of these have been constructed since 2002 during

---

[6] Figures are provided for number of measures allocated funding, rather than number of dwellings retrofitted. Roof insulation was the most popular single measure with 82,973 grants awarded from June 09-Dec 11

Irelands property boom and therefore, though not state of the art in energy efficiency terms, will not be as economical to retrofit or have the same scope for “shallow” retrofit improvements as older, poorer performing dwellings. In its initial phase, from 2011-2013, the BEH has continued broadly in line with the practices of the HESS, continuing direct subsidies for specific residential retrofit measures. For the initial 3 year phase of BEH responsibility for delivering 50% of the targeted savings in the residential sector falls on energy suppliers, and they will correspondingly be allocated 50% of the funds available, with the remaining 50% of savings and funding expected to be achieved by home owners and energy service companies. Though the targets set for energy suppliers are not legally binding they are bound to make “reasonable endeavours” to achieve them.

The scale of the proposed works necessary to meet the ambitious targets set for the period to 2020, along with national financial constraints, means that it will no longer be financially viable for the exchequer to directly subsidise householders for works undertaken after the initial 2011-2013 period. From 2014 onwards, the focus will shift from grant support to a more market-based approach to promoting residential retrofit. The Government has committed to bringing forward a Pay As You Save scheme by that time to provide the financial support that will be necessary to encourage the uptake of retrofit works at the scale required to meet the target, and other innovative financial mechanisms such as Green Bonds may be considered [6, 107]. The EED sets a target for Energy Suppliers to save at least the equivalent of 1.5 per cent of annual energy sales to final customers per annum, excluding transport for the 2014-2020 phase[100].

At the time of the submission of NEEAP1, the BE scheme was not included as a specific measure. The target for energy savings from BE is set on the basis of the need to bridge the 8,000 GWh gap identified in NEEAP1, rather than on an assessment of the full potential for energy savings to be achieved in this area. The NESC secretariat report reviewing Irish climate policy notes that “*efficiency targets for buildings reflect the need to meet Ireland’s energy efficiency objectives, not the availability of cost-effective abatement, nor what would be required to meet climate policy objectives.”.* Current targets for BEH are for 5,200 GWh energy savings in 2020, with an initial three-year energy savings target of 2,000GWh for the period 2011-2013[6, 106].

4.3 Modelling Methodology

4.3.1 Overview

The modelling approach adopted here is a bottom-up engineering archetype model, which lends itself to analysing policy measures that have a technical focus such as building regulations or retrofitting. A full description of the modelling methodology used for this analysis is provided in Chapter 3 and a summary of the main features of the model is given here.

Reviews of the various different types of energy models employed in the residential sector has been carried by a number of authors[12, 19, 65, 66]. Swan and Ugursal describe the characteristic approach of the bottom up archetype method as follows: "*This technique is used to broadly classify the housing stock according to vintage, size, house type, etcetera. It is possible to develop archetype definitions for each major class of house and utilize these descriptions as the input data for energy modelling. The energy consumption estimates of modelled archetypes are scaled up to be representative of the regional or national housing stock by multiplying the results by the number of houses which fit the description of each archetype*". In line with this approach we first establish a set of dwelling archetypes that adequately characterise the entire dwelling stock. For each archetype dwelling we then estimate the number of dwellings existing in the base year, the number of dwellings available for retrofit in each subsequent year and the number of dwellings retrofitted each year. We also model the energy savings potential for a number of retrofit measures and combinations of measures on each archetype. The total energy savings equal the product of the number of dwellings retrofitted by the energy savings per retrofit, summed across all retrofit measures and across all archetypes.

4.3.2 Archetypes

In order to establish a set of archetype dwellings that can adequately describe the wide range of existing dwelling types we classify dwellings by three main characteristics: building type, energy performance and wall construction type. Under each of these headings we further subdivide dwellings into a number of categories, a full list of the subdivisions is given in Table 4.1. Data on each of these characteristics was taken from the NAS database of BER results. The five building types chosen represent the most common building forms in the Irish residential sector which between them account for 87% of dwellings recorded in the NAS database. The seven energy performance ratings correspond to the letter bands specified by the BER scale, on which more information is given in Table 4.2

Wall construction type is an important consideration as it affects what wall insulation retrofit measures it is possible to implement. This has significant cost implications and has historically been a deciding factor as to how likely a dwelling is to undergo retrofit. Five wall construction types were chosen to reflect the wide range prevalent in the dwelling stock, these were Un-Insulated Cavity Walls (UICW), Un-Insulated Solid Walls (UISW), Partially Insulated Solid Walls (PISW), Insulated Walls (IW) and Highly Insulated Walls (HIW). A full description of the analysis carried out to determine appropriate wall construction type categories is given in chapter 3. The key factors considered were the presence or absence of a wall cavity and the degree of insulation already present, for which the existing U-Value is used as an indicator. Table 4.3 lists the wall type categories and the criteria for each.

5 Building Types	7 Energy Performance Ratings	5 Wall Construction Types	Archetypes
1 Storey Detahced	A	Un-Insulated Solid Wall	175 Archetypes
2 Storey Detached	B	Partially Insulated Solid Wall	
2 Storey Semi Detached	C	Un-Insulated Cavity Wall	
2 Storey Terraced	D	Insulated Wall	
1 Storey Apartment	E	Highly Insulated Wall	
	F		
	G		

Table 4.1: *Dwelling Archetypes*

NAS	Label	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	E1	E2	F	G
	kWh/m^2/annum	<25	>25	>50	>75	>100	>125	>150	>175	>200	>225	>260	>300	>340	>380	>450
Model	Label	A			B			C			D		E		F	G
	kWh/m^2/annum	<75			>75			>150			>225		>300		>380	>450

Table 4.2: *BER Bands*

Description	Abbreviation	Cavity/Solid Wall	U Value Range
Un-Insulated Cavity Wall	UICW	Cavity	U>0.6
Un-Insulated Solid Wall	UISW	Solid	U>1.78
Partially Insulated Solid Wall	PISW	Solid	0.61≤U≤1.78
Insulated Wall	IW	Cavity & Solid	0.38≤U≤0.6
Highly Insulated Wall	HIW	Caivty & Solid	U<0.38

Table 4.3: *Summary of Wall Construction types*

4.3.3 Numbers of dwellings available for retrofitting

The total number of dwellings in each archetype category in the base year, 2011, is calculated using data from the NAS BER database and from the Central Statistics Office (CSO) national census of 2011. The resulting number of dwellings by wall construction type is given in Table 4.4.We assume that in each archetype category there will be a certain small percentage of dwellings that will not be available for retrofitting and will not become obsolete in the time frame considered. We assume this figure to be 5%. From the base year on, the number of dwellings available for retrofit in a given year is reduced annually through obsolescence and through the uptake of retrofit measures. We assume that once a dwelling has undergone one phase of retrofitting it will not go to the expense and inconvenience of another within the timeframe considered. This implies that there is only one opportunity for achieving retrofit improvements for a given dwelling and results in a lock in effect, whereby implementing shallow retrofit measures comes at the cost of excluding the implementation of deeper retrofit measures at a later stage.

The annual numbers of dwellings to be retrofitted is based on the targets set for the BEH scheme. Due to the ambitious nature of the targets that have been set and recent grant uptake rates, we also investigate the effect of substantially lower number of dwellings undertaking retrofit measures. This is dealt with further in the scenario analysis section. The rate of obsolescence is set at 0.73% of the total dwelling stock per annum, based on a previous estimate by the Department of the Environment [50]. The total number of dwellings in the housing stock from 2011 to 2020 is taken from projections by the Economic and Social Research Institute (ESRI). 0.73% of this total figure is subtracted annually from the number of dwellings existing as of 2008, assuming that no dwellings constructed after 2011 will become obsolete within the time frame.

	UISW	UICW	PISW	IW	HIW	Total
Number of dwellings existing, 2011	175,776	112,229	168,344	472,030	721,027	1,649,408
Number of dwellings available for retrofit and obsolesence, 2011	166,988	106,618	159,927	448,429	0	881,962

Table 4.4: *Numbers of dwellings by wall type in base year*

4.3.4 Apportioning dwellings for obsolescence and retrofit between archetypes

For a given number of dwellings to be retrofitted or made obsolete, it is necessary to decide which, if any, archetypes are more likely to be retrofitted or made obsolete than the others. We use wall type as the factor on which to weight dwelling archetypes as being more or less likely to undergo retrofit or become obsolete, based on analysis that suggests it has been an important factor in the past. Table 4.5 shows the breakdown of measures applied for and completed under HESS, based on a survey by SEAI [88], along with the level of grant support provided. Of the three types of wall insulation it can be seen that cavity wall is significantly cheaper than internal or external wall insulation. The average spend under the HESS, including grant was just €2,900 resulting in a large uptake of shallow measures, such as roof and cavity wall insulation and a low uptake of more expensive measures such as external wall insulation. Typically, cavity wall insulation is used on UICW dwellings while external/internal wall insulation can be used on any wall type and are typically used for retrofitting UISW and PISW dwellings. Of dwellings that undertook some form of wall insulation, 90% undertook cavity wall insulation, leading to a heavy weighting towards UICW dwellings undertaking retrofit works in the past. In making assumptions regarding the shares of dwellings to be retrofitted by different archetypes, we use this past performance as a starting point. We assume that all future dwellings to be retrofitted will undergo some form of wall insulation. From Table 4.5, we assume all cavity wall insulation was installed in UICW dwellings and that internal and external was installed equally amongst UISW and PISW dwellings. This gives an initial ratio of 5% UISW, 90% UICW, 5% PISW for dwellings undertaking retrofit works, as shown in Figure 4.1.

Obsolescence in the Irish dwelling stock is poorly understood, both in terms of the absolute numbers and also the type of dwellings that are being made obsolete. In light of this sensible assumptions have to be made to populate the model. Generally, UISW dwellings will be older, of poorer BER rating and more expensive to retrofit than other wall construction types, therefore we assume that these dwellings will be more likely to become obsolete. Similarly we assume that IW are unlikely to become obsolete and that no HIW will become obsolete over the time horizon. UICW and PISW are assumed to be equally likely to become obsolete. We assume an initial ratio of 20% UISW, 60% UICW, 20% PISW dwellings, as shown in Figure 4.1. Only when there are no dwellings available in any of these three archetypes would dwellings in the IW archetype start to become obsolete.

HESS Measures	Grant €	Approximate Cost €	% of participants applied for	% of participants completed
Roof Insulation	200		84	70
Cavity Wall Insulation	320	1,200	61	53
Heating Controls Upgrade	400		7	4
High Efficiency Gas Boiler & Heating Controls Upgrade	560	2,800	19	15
High Efficiency Oil Boiler & Heating Controls Upgrade	560	2,800	17	10
Internal Wall Dry-Lining	2,000	9,000	8	4
External wall insulation	4,000	20,000	4	2

Table 4.5: *Applications and uptake of measures in HESS*

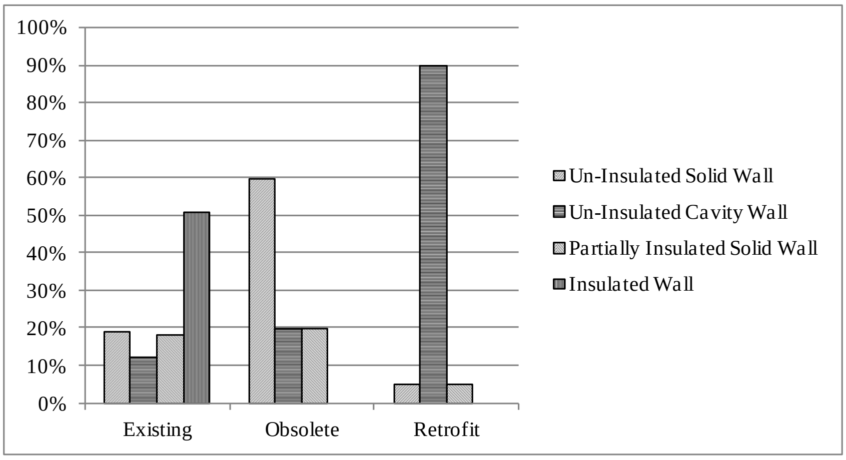

Figure 4.1: *Percentage of dwellings assumed obsolete and retrofitted in 2012, by wall type.*

4.3.5 Energy demand of archetype dwellings

The energy demand for each of the individual archetype dwellings was calculated using the DEAP software package discussed in section 4.2. DEAP is a building physics model based on IS EN 13790 [43] and draws heavily on the calculation procedures and tabulated data of the UK Standard Assessment Procedure (UK-SAP) [44]. The procedure takes account of space heating, water heating, ventilation and lighting calculated on the basis of standard occupancy, heating patterns, internal and external temperatures etc, as well as reduction in imported energy due to sustainable energy generation technologies[83, 84]. It requires as inputs a detailed description of the physical characteristics of the dwelling. We again made use of the NAS BER database to populate the model with the required data for each of the archetypes.

4.3.6 Realised energy savings relative to technical energy savings potential

Section 3.7 discusses the concepts of pre-bound and rebound in relation to deterministic heat flow models such as DEAP or UK-SAP. In brief, the “pre-bound” effect is a collective term for a number of model inaccuracies that lead to a difference between predicted and actual energy consumption in the base case. These include inaccuracies in the input data, in the assumptions made regarding occupant behaviour and in the algorithms used for the calculation. The direct rebound effect refers to the situation whereby a number of the key operating variables determining energy consumption change as a direct result of the increased efficiency of the building and have a counteracting effect.

Detailed analysis of the rebound effect across the whole BEH scheme has not been carried out as part of this work. Rebound effects are complex and the subject of an expansive field of research in their own right. To give just one recent relevant example Chitnis et al [22] looked at the rebound effect due to the retrofitting of the UK residential stock with a number of measures similar to the ones considered in this work including roof insulation, cavity wall insulation, boiler upgrade and solar thermal water heating. They differentiate between direct and indirect rebound effects, energy versus emissions rebound effects, energy efficiency versus energy sufficiency rebound effects, direct versus embodied energy emissions rebound, and finally income versus substitution rebound effects. They conclude that direct and indirect rebound effect potential is in the range of 5 to 15%, and is due mostly to indirect rebound effects. The model presented here does not explicitly account for rebound effects, and therefore the technical energy savings potential calculated must be considered as an upper bound on the savings likely to be realised.

4.3.7 Energy savings from individual retrofit measures

We modelled the energy savings potential of six individual retrofit measures. The energy savings potential of each of these measures on each of the archetypes were calculated using DEAP calculations for each archetype before and after retrofit. These were: roof insulation, cavity wall insulation, solid wall insulation, boiler and heating controls upgrade, solar hot water and high performance windows. Solid wall insulation here refers to either internal or external wall insulation. These two technologies are grouped because they are applicable to the same archetype categories, i.e. dwellings for which cavity wall insulation is not suitable, and they can achieve similar final U-values.

4.4 Scenario Analysis

4.4.1 Numbers of dwellings retrofitted

BE has specified the aim of retrofitting 1 million domestic, public and commercial buildings between 2011 and 2020. A specific total number of residential dwellings to be retrofitted is not specified but SEAI have indicated a target of 100,000 retrofits per annum and the height of the scheme. The NESC secretariat report notes that SEAI data suggests in the region of 2,000 non-residential buildings would be retrofitted, which in turn suggests that the government envisages virtually all of the 1 million buildings to be retrofitted in the period to 2020 will be residential dwellings. In their analysis NESC assume what they consider to be a conservative figure of 900,000 residential retrofits[6].

Referring to Table 4.4 we can see that 721,027 dwellings are in the HIW category. The HIW archetypes represent dwellings that have been built to the latest building regulations or have already had retrofit works carried out. For this reason we have assumed that none of these dwellings will become obsolete or undergo retrofit over the time horizon considered. The archetypes that we have assumed would be most likely to undergo retrofit are UICW, UISW and PISW dwellings, of which in total there are 456,350 dwellings in 2011. Adding to this IW dwellings gives a total of 928,381 dwellings available for retrofit and obsolescence. We further assume that it will be impossible to retrofit 100% of any archetype as there will always be a small proportion of dwellings that will not or cannot partake in any scheme. We optimistically assume that 95% of dwellings in a given archetype will be available for retrofit or obsolescence, which gives a total of 881,962 dwellings. The estimated number of dwellings made obsolete over the time period is 113,872, leaving the total number of dwellings available for retrofit at 768,090. Based on this we assume that a realistic upper bound on the numbers of dwellings to be retrofitted in the period 2012 to 2020 would be 750,000, which would involve retrofitting all the available UICW, UISW and PISW dwellings along with 89% of IW dwellings. We refer to this as the 750k scenario. Although less than the Government estimates, this is still ambitious considering the large amount of IW dwellings that will need to be targeted. The majority of dwellings in the IW category (62%) have C or better energy performance ratings with just under 18% achieving A or B ratings and 37% of IW dwellings have been built in the period post the year 2000, a reflection of the large expansion in dwelling construction during Irelands recent building boom. Being of recent construction, and reasonably well insulated to begin with, many of these IW dwelling would be unlikely to undergo retrofit, in particular those achieving A and B BERs.

We consider a second scenario where only half as many dwellings as the previous 750k scenario are retrofitted. This is based on recent trends in uptake of grant support for retrofit, which saw a maximum uptake of approx 35k dwellings per annum [103]. This scenario would correspond to retrofitting all the available UICW, UISW and PISW dwellings along with 9% of IW dwellings, and thus reflects the risk of not engaging with the occupants of IW dwellings who have perhaps not been as likely to undergo retrofit in the past on the basis that their dwellings had some reasonable level of insulation already present. We refer to this as the 375k scenario.

Due to the large number of dwellings that are to be retrofitted certain archetypes will become exhausted within the time horizon, that is the number of dwellings available for retrofit will fall to zero. When this happens the excess of retrofits will be moved onto the next most likely archetype to undergo retrofit or obsolescence, until they too become exhausted, and so on. For the 750k and 375k scenarios this results in the following profiles for the percentage of dwellings retrofitted by wall type shown in Figure 4.2, along with the numbers of dwellings remaining available for retrofit in each year.

	Thousands of dwellings retrofitted										
Scenario	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
750k	0	50	100	100	100	100	100	100	70	30	750
375k	0	25	50	50	50	50	50	50	35	15	375

Table 4.6 *Numbers of dwellings retrofitted*

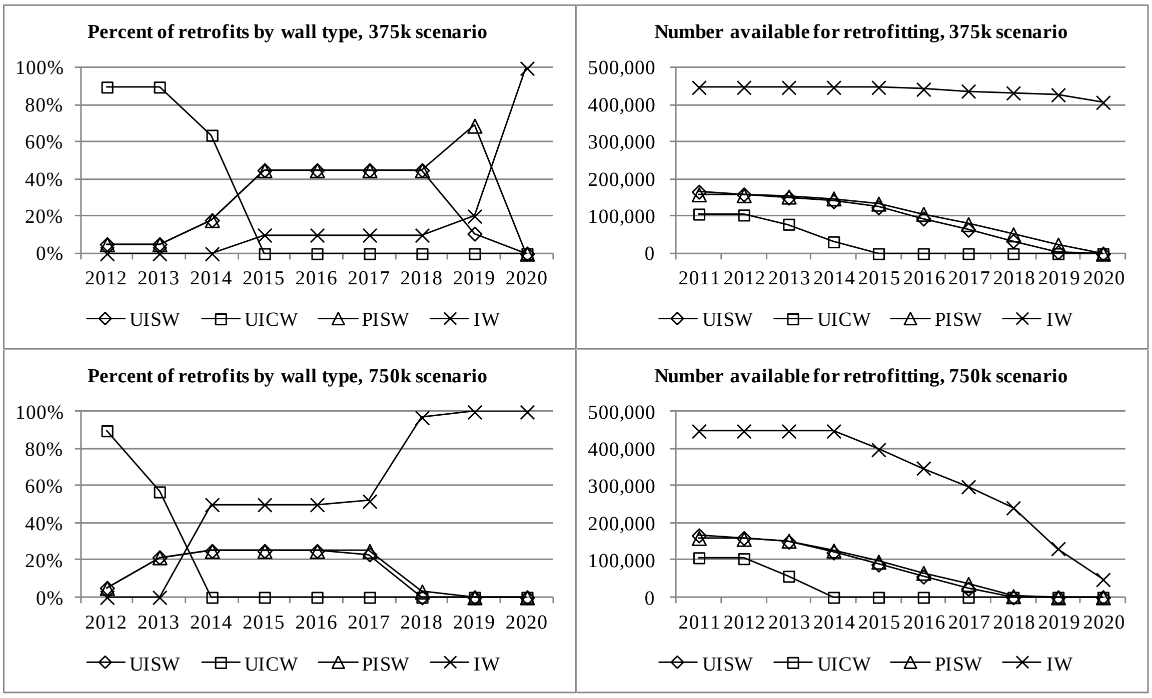

Figure 4.2: *Percentage of dwellings retrofitted and number of dwellings available for retrofit by wall type.*

4.4.2 Packages of retrofit measures

We modelled the effects of 6 individual retrofit measures as discussed in section 4.3.7. For the scenario analysis we consider the savings potential of implementing various packages of these measures. Four packages are chosen, each entailing an increasing depth of retrofit from the last. In general the terms shallow and deep retrofit are applied loosely to indicate the scale of the work carried out on a particular dwelling and the energy efficiency improvements achieved. A deeper retrofit typically entails costlier works and achieves greater energy savings. The scenarios we use here for depth of retrofit are as described below and further in Table 4.7:

- Shallow: With reference to Table 4.5, this scenario assumes that only the two cheapest and historically most popular measures would be implemented across all dwellings undergoing retrofit. These are roof insulation and cavity wall insulation. We assume that cavity wall insulation will only be installed in UICW dwellings.
- Deeper: This scenario assumes that along with the measures from the Shallow scenario, two extra measures entailing medium levels of cost and intrusion would also be implemented. These were

upgrade to a high efficiency boiler and improved heating controls, and installation of solar thermal water heating. Solar water heating was not included in the HESS but was supported by a parallel scheme to promote renewable energy technologies in the residential sector known as the Greener Homes Scheme, and is currently supported under BEH, with a grant allowance of €800.

- BEH Max: This scenario assumes that all the measures supported under the BEH scheme are implemented, including solid wall insulation which accounts for the two most expensive BEH measures, internal and external solid wall insulation. It was assumed for this scenario that solid wall insulation would only be installed in UISW and PISW dwellings, but not IW as the latter already have a reasonable degree of insulation and it was assumed would only pay for further upgrade works in the deepest retrofit scenario.
- Further: This is the deepest retrofit scenario and assumes the implementation of all available measures on all archetype dwellings. This includes all the measures accounted for in the previous scenarios, as well as upgrade to high performance windows, which is not currently supported by any scheme, as well as the installation of further wall insulation on IW dwellings.

Scenario:	UISW	UICW	PICW	IW	HIW
Shallow	Roof Insulation	Roof Insulation	Roof Insulation	Roof Insulation	None
		Cavity Insulation			
Deeper	Roof Insulation	Roof Insulation	Roof Insulation	Roof Insulation	None
	Boiler Upgrade	Cavity Insulation	Boiler Upgrade	Boiler Upgrade	
	Solar Hot Water	Solar Hot Water	Solar Hot Water	Solar Hot Water	
		Boiler Upgrade			
BEH Max	Roof Insulation	Roof Insulation	Roof Insulation	Roof Insulation	None
	Boiler Upgrade	Cavity Insulation	Boiler Upgrade	Boiler Upgrade	
	Solar Hot Water	Solar Hot Water	Solar Hot Water	Solar Hot Water	
	Solid Wall Insulation	Boiler Upgrade	Solid Wall Insulation		
Further	Roof Insulation	Roof Insulation	Roof Insulation	Roof Insulation	None
	Boiler Upgrade	Cavity Insulation	Boiler Upgrade	Boiler Upgrade	
	Solar Hot Water	Solar Hot Water	Solar Hot Water	Solar Hot Water	
	Solid Wall Insulation	Boiler Upgrade	Solid Wall Insulation	Windows	
	Windows	Windows	Windows	Further Wall Insulation	

Table 4.7: *Description of scenarios*

4.5 Results

Combining the four packages of measures with the two numbers of retrofits gives eight final scenarios for which the results are presented here and are shown in Figure 4.3 and Table 4.8. The results shown represent the technical energy savings potential. They do not take into account any form of rebound effect, and as such represent an upper bound on the savings that could be achieved for the given set of assumptions.

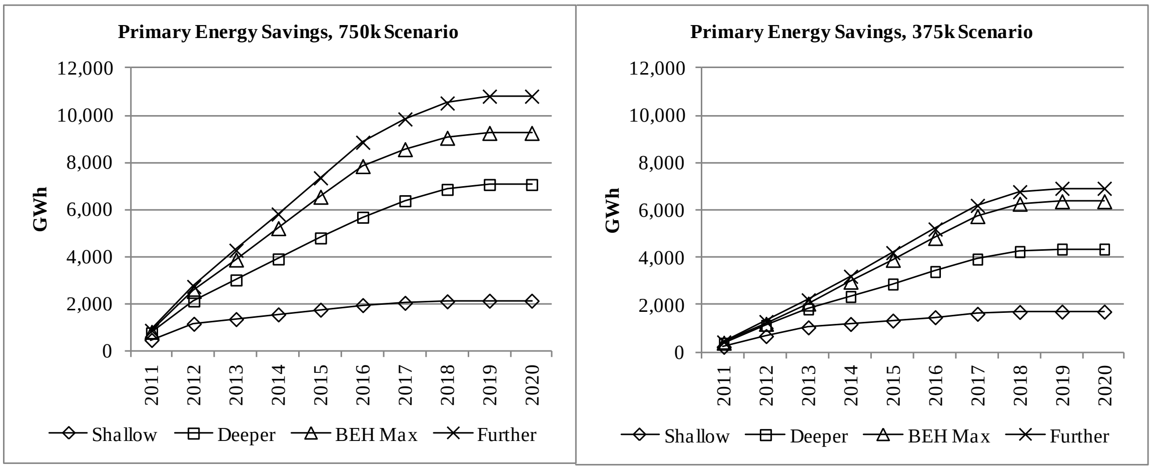

Figure 4.3: *Primary energy savings (GWh) from BEH, for all scenarios*

Energy Savings in 2020, GWh		
Scenarios	375k	750k
Shallow	1,713	2,123
Deeper	4,358	7,062
BEH Max	6,379	9,255
Further	6,929	10,817

Table 4.8: *Primary energy savings in 2020 (GWh) from BEH, for all scenarios*

4.6 Discussion

In the extreme upper bound scenario we find a technical energy savings potential of 10,817 GWh is possible. This will require a significant shift in emphasis on two fronts. First in terms of the types of dwellings being retrofitted, shifting from UICW and UISW and PISW dwellings to largely IW dwellings. Secondly, in terms of the depth of retrofit measures carried out, from relatively shallow, cheap, convenient measures such as roof and cavity wall insulation, to deeper, more expensive, inconvenient and intrusive measures such as solid wall insulation and installation of high performance windows. To achieve both of these aims would be challenging. At the lower end of the scale, if current trends were to continue, i.e. shallow retrofit measure being carried out on a maximum of 50,000 dwellings per annum, involving the eventual retrofit of all UICW, UISW and PISW dwellings but with relatively little uptake from IW dwellings, the maximum technical savings potential would be reduced to1,713 GWh. The key in moving from the lower to the upper estimate will be the success in leveraging far more capital, as well as time and effort, from participants. This has been recognised by the government and proposed changes to the structure and funding mechanisms behind the BEH scheme in the second phase of its implementation from 2014 to 2020 are intended to encourage participants to be more ambitious and embark on deeper retrofit measures [107]. How successful these measures will be in bringing about these shifts in behaviour in what remains a difficult economic environment remains to be seen. Based on recent uptake of grants and the uncertainty involved in moving from a grant based scheme to more market based mechanisms, the authors feel the likely potential is more likely to fall within the lower end of the range, i.e. between 2,000 and 4,000 GWh.

Although from a purely energy savings/carbon abatement view point all forms of rebound are negative as they reduce the realised savings below the maximum theoretical energy savings potential, some of the direct rebound effects of residential retrofit have important benefits to the individual dwelling occupants and to society. For measures aimed at increasing the energy efficiency of residential space heating direct rebound is as a result of occupants realising a proportion of the energy efficiency improvements as an increase in internal temperature and comfort levels rather than as a decrease in energy consumption and associated fuel costs. This increase in internal temperature can have important and economically valuable societal benefits in terms of reduced morbidity and increased quality of life, and this should be considered when evaluating the effectiveness of such measures[70, 72, 73]. Direct rebound such as this is more likely to be evident from the retrofitting of dwellings with poorer initial energy performance ratings in the UISW, UICW and PISW categories which are more likely to have lower than desired initial internal temperatures. Indirect rebound effects relate to using the money saved from lower energy consumption on increased consumption of goods and services in other areas of the economy. As discussed by Chitnis et al these effects can cause greater rebound than direct effects. They are more likely to occur through the retrofitting of dwellings with better initial energy performance ratings from the IW category, as these dwellings are more likely to already have adequate internal temperatures[18].

4.7 Conclusions

This paper estimates the technical energy savings potential in the Irish residential sector due to the introduction of an ambitious national residential energy efficiency retrofit programme known as Better Energy Homes. In the year 2020, the estimated technical energy savings potential lies in the range of 1,713 GWh to 10,817 GWh. Based on recent uptake of grants and the uncertainty involved in moving from a grant based scheme to more market based mechanisms it is more likely to fall within the lower end of this range, i.e. between 2,000 and 4,000 GWh. This compares with target savings for the scheme of 5,200 GWh, which appears unlikely to be achieved. The two key factors determining the success of the scheme will be the number of dwellings retrofitted and the average depth of retrofit works carried out. Although the scheme targets the retrofit of almost 1 million dwellings our analysis suggests that 750,000 would be a more realistic upper bound. The trend under the HESS scheme was for the uptake of shallow retrofit works and if this were to continue then even with the retrofit of 750,000 dwellings there would be a significant shortfall from the 5,200 GWh target. A key challenge for policy makers will be to enact a policy framework that is successful in leveraging greater investment in deeper retrofit measures from participants, both home owners and energy supply companies. This work presents the technical energy savings potential of the scheme and does not account for potential direct or indirect rebound effects. The authors conclude from this analysis that the target of 5,200 GWh energy savings is technically feasible but very challenging and unlikely to be achieved. It will require close to 750,000 dwellings, or virtually all dwellings not already in the Highly Insulated Wall category be retrofitted and will require a very significant shift towards deeper retrofit measures than is currently the trend.

Chapter 5

5 LEAPs and Bounds – A Hybrid Energy Demand and Constraint Optimized Model of the Irish Energy System

5.1 Introduction

The Ireland LEAP project was initiated by the Sustainable Energy Authority of Ireland (SEAI) in 2009 to develop bottom up modelling capability of energy demand in Ireland (SEAI 2009), in order to complement the existing national energy forecasts prepared by SEAI which are predominantly based on a top down methodology. A key goal of the project was to improve the capacity for modelling in a bottom up fashion energy savings due to policy measures which have a technical focus, such as improved building regulations for the residential sector. The modelling tool that was proposed to facilitate this work was the Long range Energy Alternatives Planning system (LEAP). The potential role in Ireland for LEAP as an energy planning tool has been acknowledged in Ireland's national energy forecasts: "The long-term vision is to use LEAP-Ireland as a planning tool for assessing the future impacts of possible energy efficiency policies and measures, complementing and providing an alternative perspective to ongoing macro-economic modelling" [24].

This chapter presents the work carried out by the University College Cork Energy Policy & Modelling Group as part of the Ireland LEAP project. It provides an overview of the full energy model of Ireland's economy and the broad approach taken for modelling individual subsectors, and then focuses on the modelling methodology adopted for the residential sector. Results are shown for both the overall model and in more detail for the residential sector. An overview of the chapter is as follows: Section 5.2 gives an overview of the project, including a brief description of all sectors modelled and of the LEAP-OSEMOSYS interface. Section 5.3 describes the modelling of the residential sector portion of the model in detail. Section 5.4 presents the results of the 3 scenarios developed. Section 5.5 discusses and section 5.6 concludes.

5.2 The Ireland LEAP project

5.2.1 Overview

The Ireland LEAP project builds an energy model for one country and uses it to develop a number of future energy scenarios for the period to 2020. It adopts a different approach to that used to generate Ireland's official energy forecasts [108] in that it provides more sectoral and technical detail, which is necessary in particular for modelling energy efficiency policies that are applied at a sectoral level (for example building regulations, retrofit programs for houses, performance based car taxation, etc.) [29]. The tool used in this project is LEAP. While LEAP is not new, the model developed in this project is innovative in a number of ways, namely the demand-side is constructed from sectoral sub-models with a unique modeling approach for the transport and residential sector; and, this is the first national level model developed within LEAP to combine detailed end-use analysis for the transport and residential sector on the demand side with a cost-minimizing optimization approach for modelling the electric generation sector using the Open Source Energy Modeling System (OSeMOSYS) [109] Through a detailed scenario analysis, the project analyses the aggregate impact of a number of energy efficiency policies and the potential impact of improvements in energy efficiency beyond current policy projections. As such, its primary contribution is to assessing energy policy in Ireland; however, this research has also made a valuable contribution in terms of helping to test and debug the new OSeMOSYS optimization capabilities in LEAP.

5.2.2 Modelling approach

There are many approaches to energy modelling and scenario analysis (a review lists 364 unique examples) [110], while the different methodologies, data-requirements, types of problem to be solved range from the simple to the exceedingly complex [111]. Categorization in terms of what is modelled (energy demand, energy supply and the energy system) and the modelling approach used (econometric, techno-economic, partial and general equilibrium, simulation, optimization and end-use accounting) [112] leads to a complex taxonomy of models. A simple distinction is often made between a bottom-up approach, which is more data intensive and more appropriate for detailed analysis of individual energy policies and a top-down approach, which has a more econometric approach and uses less technology explicit data [113]. Despite the distinction being widespread, the two categories of bottom-up and top-down aren't mutually exclusive, there also exists a "hybrid" class where the two approaches are combined; one of the main contributions of the hybrid approach is the detection of missing information and dynamics that simple top-down or bottom-up models cannot detect on their own [13]. For this project a combination of bottom-up and top-down techniques were used for different subsectors of the economy as appropriate. It does not classify as a hybrid modelling approach however, as each sector was modelled using either a top-down or bottom-up approach, rather than a combined approach.

The Ireland LEAP model can broadly be broken down into an energy demand side and an energy supply side. The energy demand side is further subdivided by sector into industry, services, residential and transport. The energy supply side is comprised of energy resources, electricity generation, and transmission and distribution. A distinction is made between model generation and model data entry: the energy demand part of the model started as a *tabula rasa* where the first step was to design a structure and then within each of these sectors, owing to varying data availability and different scenario analysis requirements, a unique modelling approach and design was required. For the electricity generation sector, the model structure was in place at the outset and so the work required to complete a fully functioning model was appropriate data characterization of the electricity generating units and assumptions about the expansion of the electricity system's generation capacity over time.

5.2.3 Bottom-up modelling

One of the main uses of the Ireland LEAP model is for modelling the explicit impact of individual energy efficiency policies. Because many of the policies are technical in nature (e.g. changes to MJ/km or kWh/m^2/yr) and they target a particular sector (e.g. low mileage passenger cars or low energy-rated dwellings), a bottom-up approach is adopted for two sectors (residential & transport) that have sufficient high-quality data available. In most cases the data used is publically available and is specific to the local conditions in Ireland; otherwise, data-proxies or data from other countries are used. The projections for energy demand in each bottom-up sector are based on existing and future technical characteristics of the individual energy consuming unit and in all cases, these projections are linked to macro-economic activity metrics such as GDP, GNP or house numbers that were the output generated by a separate macro-economic model [114].

5.2.4 Top-down modelling

For the two top-down sectors (services & industry) in the Ireland LEAP model, energy demand is derived from an elasticity with Gross Added Value (GVA) as an activity variable: for services, GVA is associated with the sector in-aggregate and for industry, GVA is linked with each sub-sector. This econometric-type approach is better suited to sectors which are more closely linked to economic activity such as industry [115]. In the Ireland LEAP model, the same exogenously derived macro-economic activity variables that were used in the bottom-up sectors are used in the top-down sectors and in this way the two separate approaches are consistent. While top-down modelling based on regression analysis of historical trends can be used to generate a general trend of energy efficiency, the baseline will still incorporate many distorting factors, such as the impact of past investment in energy efficiency technologies and this must be borne in mind when comparing an energy efficiency scenario with a baseline scenario, in order to isolate the impact of energy efficiency [115].

5.2.5 LEAP & OSeMOSYS

While it is possible to build an energy systems model entirely from first principles using energy flow equations, energy end-use consumption rates and activity rates, there are a number of off-the-shelf computer packages that provide a framework for building a model, running scenarios and generating results for analysis. LEAP is a widely-used software tool for energy policy analysis and climate change mitigation assessment developed at the Stockholm Environment Institute [116]. It is an integrated modelling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy. LEAP can be used to account for both energy sector and non-energy sector greenhouse gas (GHG) emissions as well as local and regional air pollutants. It can also be used as a comprehensive accounting system for conducting integrated cost-benefit analyses of energy scenarios. LEAP has been adopted by hundreds of organizations in more than 190 countries and its users include government agencies, universities, non-governmental organizations, consulting companies and energy utilities. LEAP has been applied at many different scales ranging from cities and states to national, regional and global applications. While LEAP is less sophisticated than other energy modelling tools such as MARKAL [117], TIMES [118] or MESSAGE[119], its contribution primarily lies in its flexibility, transparency and ease-of use and its emphasis on data management and reporting as much as on its modelling algorithms [111]. LEAP has been used in over 70 peer-reviewed journal papers [120] for a variety of modelling problems [121-124]and it has also been used to inform policies for achieving an 80% cut in GHG emissions in Massachusetts [125]. LEAP has been variously described as a bottom-up model [110], an accounting model [126] and a top-down model [120]; however, different approaches can be mixed and matched within a single model and this paper demonstrates a combination of a bottom-up approach and a top-down approach.

The most recent version of LEAP[7] now functions with Open Source Energy Modelling System (OseMOSYS). While OSeMOSYS is capable of modelling the entire energy system in a stand-alone capacity, within LEAP it is applied specifically to calculate least-cost capacity expansion and dispatch pathways for the electricity generation sector, based on minimizing the overall cost of providing energy services. The OSeMOSYS code has been explained in greater detail elsewhere [109, 127].

5.2.6 Scenario analysis of Irish energy policy

Through its facilitation of scenario analysis, LEAP enables the evaluation of energy efficiency policies by comparing their energy requirements, costs, benefits and their environmental impacts to a baseline or reference scenario. Individual policy measures can be generated into individual scenarios, which can in turn be combined (in different combinations and permutations) into alternative aggregated scenarios. The base year for the Ireland LEAP model is 2008 and the scenario modelling period is 2009-2020, which is the same modelling period as Ireland’s National Energy Efficiency Action Plan (NEEAP) [33]. The scenarios developed in the Ireland LEAP model have a quantitative basis although some of the choices for the integrated scenarios are qualitative or expert-based. There are three overall scenarios, each of which is an aggregate of a number of scenarios modelling specific policy measures in specific sub sectors. The aggregate scenarios can be described as follows:

[7] 2012.0.0.24

- *Reference scenario:* Expected energy consumption excluding the impact of future government targets or energy efficiency policies. Its main purpose is to enable quantification of the impact of the energy efficiency scenario and energy efficiency+ scenario.
- *Energy Efficiency scenario:* Expected cumulative impact of all the sector-specific scenarios on energy consumption for a selection of current or proposed energy efficiency policies at probable implementation rates. Many of the energy efficiency policies in this scenario are in Ireland's NEEAP.
- *Energy Efficiency+ scenario*: Includes the impact of all policy scenarios from the energy efficiency scenario; it also includes the impact of certain energy efficiency policies beyond their current rate of implementation in the transport and residential sectors. It also explores the impact, in the absence of any government policies, of changes in the structure and intensity of current energy demand in the transport and industry sectors.

For the aggregate energy efficiency and energy efficiency+ scenarios, details for individual policy measures modelled within each sector and sub-sector are shown in Table 5.1. The following sections in this chapter focus only on the residential subsector on the energy demand side of the model, though some results for the overall model are presented in brief. A full description of all other aspects of the modelling work carried out for the Ireland LEAP project can be found in [25]

Aggregate Scenario	Sector	Sub-Sector	Policy	Description
Reference	All	All	business-as-usual	business-as-usual
Energy Efficiency	Transport	Private Cars	electric vehicles: average	10% EV penetration by 2020, EVs replace cars with average mileage
		Private Cars	mileage reduction	Mobility management causes mileage reduction of private cars
		Private Cars, Taxis & Hackney, Buses	efficient driving	Improved vehicle efficiency for all road vehicles due to better driving
	Residential	Space & Water Heating: New Dwellings	building regulations 2011	Rollout of 2011 building regulations
		Space & Water Heating: New Dwellings	building regulations 2015	Rollout of 2015 building regulations
		Space & Water Heating: Existing Dwellings	retrofit: average	Retrofit of 800,000 dwellings, average retrofit depth
		Lighting & Appliances	CFL lighting	Full penetration of more energy efficient CFL bulbs
Energy Efficiency+	Transport	Private Cars	high efficiency vehicles	New cars are efficient so average emissions by 2020 are 95g CO2/km
		Private Cars	electric vehicles: best	10% EV penetration by 2020, EVs replace cars with high mileage
		Private Cars, Trains, Buses	modal shift	cars to public transport (train & bus)
		Private Cars	private car occupancy	Increase in private car occupancy from 1.93 to 2.5
	Residential	Space & Water Heating: Existing Dwellings	retrofit: best	Retrofit of 100,000 dwellings, deep retrofit
	Industry	All NACE categories	GVA change	20% GVA increase in one sub-sector & 25% GVA decrease in other sub-sector
		All NACE categories	efficiency change	Energy efficiency of all industry sub-sectors decreases by 10%

Table 5.1: *Aggregate scenarios by sector, sub-sector, policy and description:*

5.3 Residential Sector Model

5.3.1 Overview

The importance of the residential sector in the overall national energy demand balance can be seen from the fact that in 2008, it had a 25.2% share of Total Primary Energy Requirement (TPER) and a 23.8% share of Total Final Consumption (TFC), having recorded a 38.2% increase in primary energy requirement in the period 1990 to 2008. Its importance is further highlighted when considering energy efficiency measures contained within Irelands first NEEAP where the residential sector counted for 44% of the total savings identified in 2020 [33].

The overall tree structure established for the residential sector within LEAP is shown in Figure 5.1. Space and water heating are separate branches within the model but have identical tree structures and modelling methodologies, and can effectively be considered as one. The following sections give a brief description of the modelling methodology for each sub sector.

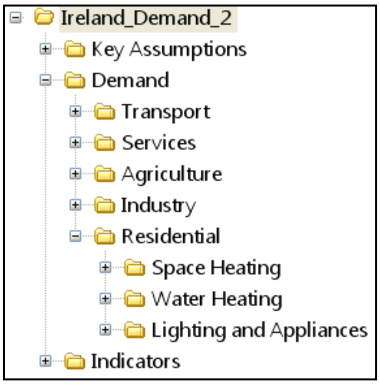

Figure 5.1: *Overall tree structure of Ireland LEAP model.*

5.3.2 Space and water heating

For the energy consumption of space and water heating an engineering archetype modelling approach was used [12]. A set number of dwelling archetypes were defined to represent all the various dwelling types in the existing and future dwelling stock. In order to achieve this the dwelling stock was first subdivided further into three sub sectors: existing dwellings, retrofitted dwellings and new dwellings. The “existing dwellings” category accounts for dwellings that were occupied as of 2008 and which, over the time horizon of the model(2009-2020) have not yet undergone retrofit works to improve energy efficiency. The “retrofitted dwellings” category accounts for dwellings that were occupied as of 2008 and which are chosen within the model to undergo retrofit works to improve their energy efficiency between 2009 and 2020. “New dwellings” include all dwellings that become newly occupied from 2009 to 2020, including dwellings that had been constructed pre 2009 but only became occupied post 2009.

5.3.2.1 Existing and retrofitted dwellings[8]

For both existing and retrofitted dwellings 35 archetype dwellings were used to characterize the dwelling stock. These consisted of five dwelling types and seven energy performance ratings. The dwelling types considered were: one storey detached, two storey detached, two storey semi detached, terraced and apartments. The energy performance ratings correspond to those used for the Building Energy Ratings (BER) scheme which assigns dwellings a rating from A-G based on a calculation of the primary energy consumption in kWh/m^2/annum [84] required to achieve a standardised internal temperature for a standardised set of weekly heating periods. This calculation is carried out at the time of sale or rent of a property and is performed using the Dwelling Energy Assessment Procedure (DEAP) [41]. Appendix B gives further detail on the DEAP calculation procedure and the BER scheme, including the standard assumptions used in the calculation for internal temperatures, heating profiles, etc.

The data gathered and results of every BER survey carried out are stored by SEAI. As of early 2011 this database contained details of 130,000 dwellings, out of a total dwelling stock of 1.6 million. From this BER database the author mined data on dwelling type, energy rating, floor area and predicted energy consumption. Energy consumption was split into 4 separate end uses : space heating main and secondary and water heating main and secondary. The main space and main water heating demand was typically supplied via the main central heating system, while secondary space heating could be from many sources e.g. electric space heaters or open fires and secondary water heating, if present, was due only to electric emersion heaters. This data was then used to construct and populate the engineering archetype energy consumption model for the existing dwelling stock. In the base year the number of existing dwellings was 1,560,416, based on data from the Central Statistics Office (CSO), and was broken down by BER band as per Table 5.2, based on BER data.

[8] As discussed in Chapter 1, the modelling work on the space and water heating of existing and retrofitted dwellings carried out for the Ireland LEAP project was the first step in the process of model development that later lead to the methodology presented in Chapter 3. The later, more complex, methodology was developed outside of the LEAP and was not re-implemented in LEAP afterward. Thus the methodology presented here is less complex in its characterisation of the stock of existing dwellings and in its modelling of retrofit measures than that in Chapter 3. Section X discusses further the practical limitations of implementing more complex archetype models within LEAP.

This number was reduced annually to account for obsolescence, that is the destruction and abandonment of dwellings, and retrofitting. The figure for natural obsolescence has been quantified by the Department of the Environment, Heritage and Local Government as 0.73% of the total housing stock per annum [50]. When a dwelling is retrofitted within the model it is removed from the existing dwellings section and added to the retrofitted dwellings section. The retrofitting of dwellings to improve their energy efficiency was modelled as a shift in BER bands., with the scale of the shift reflecting the scale of retrofit measures carried out, resulting in a reduced energy demand for the space and water heating end uses. The tree structure of the space heating-existing dwellings branch is shown in Figure 5.2.

Dwelling Type / Energy Rating	One Storey Detached	Two Storey Detached	Two Storey Semi-Detached	Terraced	Apartment
A	16	490	569	217	111
B	1856	18004	25355	32130	55877
C	20534	51629	104476	81898	102081
D	36250	41938	132397	92002	102375
E	26621	23292	85047	85629	77184
F	16183	12057	42858	50680	32209
G	32268	21067	43062	72774	39278

Table 5.2: *Numbers of existing dwellings in the Base Year*

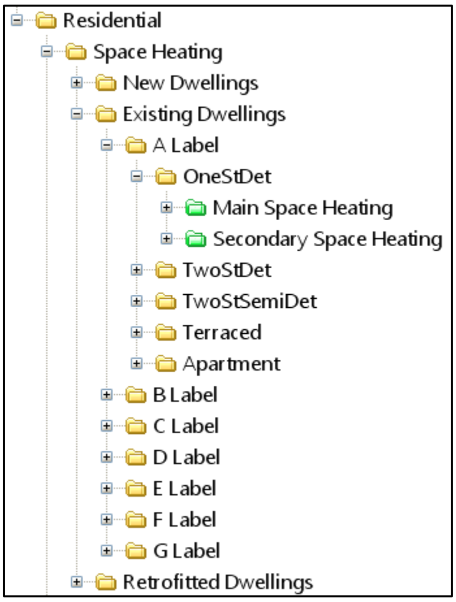

Figure 5.2: *Tree structure of space heating-existing dwellings branch of the Ireland LEAP model*

5.3.2.2 New dwellings[9]

Numbers of new dwellings were taken from projections on the total stock of dwellings made by the Economic and Social Research Institute (ESRI). The annual number of new dwellings equals the overall increase in the total number of dwellings in the stock plus the number of new dwellings required to replace obsolete dwellings. Between 2008 and 2020 the overall number of dwellings is predicted to increase from 1,560,416 to 1,941, 392, an overall increase of 380,975 dwellings. In the same time period 151,027 dwellings are predicted to become obsolete leading to the construction of 532,002 new dwellings. This significant increase in dwelling numbers

reflects the growth in the demographic drivers involved, namely a young, increasing population and falling occupancy ratios per dwelling[114], as shown in Table 5.3.

The space and water heating energy requirement of new dwellings was also modelled using the same five dwelling types as for existing dwellings, one storey detached etc. Rather than using BER grades the energy performance of new dwellings was calculated based on improvements to Part L of the Building Regulations (BR) concerning energy efficiency of dwellings, between 2009 and 2020. At the time of modelling the 2008 BR had just been introduced to supersede the 2005 BR. It was planned that these would in turn be superseded by 2010 BR (which in fact were introduced in 2011) and again by 2013 BR(which have been pushed back potentially to 2015). As such four BR were modelled, 2005, 2008, 2011, 2015. A fifth category was added to account for dwellings which were constructed prior to 2008 but which would only become occupied between 2009 and 2020. This was a particular issue in the Irish context due to the property bubble which the country experienced between 2002 and 2007 leading to a large surplus of vacant dwellings in 2008 which would reduce the demand for new dwelling construction between 2009 and 2020. This lead to 25 dwelling archetypes for new dwellings. The tree structure of the space heating-new dwellings branch is shown in Figure 5.3.

The energy demand of the dwellings built to the 2005 BR were modelled using DEAP, taking the

[9] For the energy demand of space & water heating in new dwellings the modelling methodology that had previously been devised to examine the effect of the introduction of changes to Part L of the building regulations, and which was presented in Chapter 2, was used and implemented in LEAP.

minimum elemental U-Values from the Technical Guidance Documents for Part L BR (TGDL) as inputs. The energy consumption for the equivalent 2008 and 2011 archetypes were calculated by reducing the overall energy demand by 40% and 60% respectfully in line with the targets for these regulations. A 75% reduction was assumed for the 2015BR. The details of the modelling approach for new dwellings is described further in [62].

	2008	2020
Number of Dwellings (million)	1.56	1.92
Population (million)	4.41	4.9
Occupants/dwelling	2.83	2.55

Table 5.3: *Drivers for increasing numbers of dwellings*

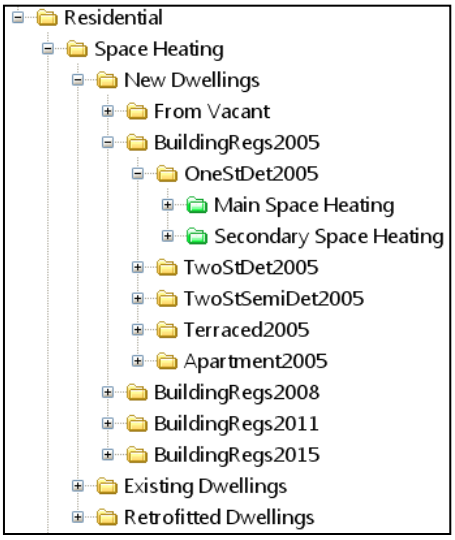

Figure 5.3: *Tree structure of space heating-new dwellings branch of the Ireland LEAP model*

5.3.3 Lighting and appliances

After space and water heating, the energy consumption of all other residential end uses is covered under the heading of “Lighting and appliances”. For the modelling of the lighting and appliances subsector again a bottom up modelling approach was used. This subsector was further sub divided into cooking, lighting, white appliances and miscellaneous electrical appliances, and each of these categories was further subdivided as shown in Table 5.4. In each case the energy consumption was modelled as the product of an activity level by an energy intensity. The activity level was modelled by considering historical data on the percentage penetration of appliances in the dwelling stock and projecting forward the historical trend to meet assumed saturation levels, as shown in Figure 5.4. Where possible data for Ireland taken from SEAI was used and where this was not available data from the UK taken from the ODYSSEE data base [1] was substituted. The energy intensity of each appliance was again projected forward using historical trends. Historical data for Ireland was not available so specific consumption data for appliances for the UK was obtained from the ODYSSEE database.

Lighting & Appliances	
Sub-sector	Energy-end-use types
Lighting	Incandescent
	CFL
Cooking	Electrical
	Natural Gas
	LPG
White Appliances	Refrigerators
	Freezers
	Clothes-washers
	Clothes-dryers
	Dishwashers
Miscellaneous Electrical Appliances	Kitchen appliances, entertainment systems, etc

Table 5.4: *Lighting, cooking and appliances energy-end-use types*

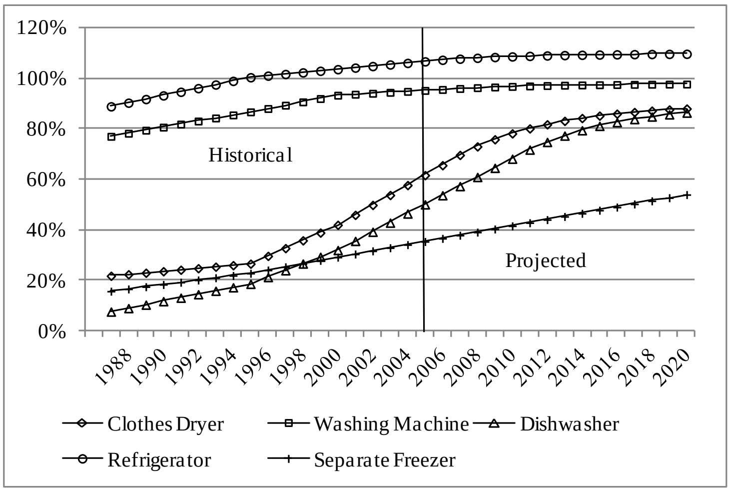

Figure 5.4: *Historical and projected penetration levels of domestic white appliances*

5.3.4 Scenario analysis for the residential sector

Section 5.2.6 describes the formulation of the 3 overall scenarios developed, reference, energy efficiency and energy efficiency+. The following section describes in some more detail the implementation of the individual policy scenarios in the residential sector.

5.3.4.1 Reference scenario

The reference scenario is designed as a baseline scenario against which the two further policy scenarios can be measured. For new dwellings it is assumed that no new building regulations are introduced after the 2008 BR, that is, all dwellings newly occupied after 2008 are either newly constructed to the 2008 BR or else from the stock of vacant dwellings. For lighting & appliances a gradual phase out of incandescent light bulbs in favour of more efficient CFL bulbs over the time period is assumed, with 75% of bulbs in 2020 being CFL.

For existing dwellings in the reference scenario, it is likely that a certain number of dwellings will undertake energy efficiency retrofit works in the absence of government policy measures or incentives; however, data on the number or extent of retrofit works carried out in private residences immediately prior to the introduction of the Home Energy Savings Scheme (HESS) in 2009 is not available. A previous study in Ireland highlighted the historical large-scale lack of investment in residential retrofit works in the absence of government policy, even when such measures would be economically beneficial to the owners [69]. The only estimate of autonomous retrofit levels available was from the National Survey of Housing Quality in 2001/02 [128], which questioned householders on whether they had undertaken upgrades to their property in the previous five years. Based on this data the authors assume that 1.4% of existing dwellings per annum will undergo a shallow retrofit in the reference case, corresponding to just under 300,000 dwellings in the period 2008-2020

5.3.4.2 Energy efficiency scenario

As described in section 5.2.6 the energy efficiency scenario represents energy efficiency policies that are currently in place, or for which there is a commitment. Many of these policies can be found in Ireland’s NEEAP [33]. For the residential sector this scenario contains 3 measures aimed at reducing space and water heating energy demand, namely the 2011 BR and 2015 BR affecting new dwellings and the retrofit programme for existing dwellings, as well as a measure to phase out incandescent bulbs in favour of CFL within lighting and appliances. For the introduction of the 2011 BR and 2015 BR scenarios we assumed that in the first year of implementation 25% of dwellings newly constructed in that year would be to the new BR, 75% in year 2 and 100% in year 3, until superseded by a later BR edition. The *CFL lighting* scenario considers the policy to upgrade all dwellings to CFL lighting by 2012 rather than just a gradual phase out, i.e. 100% of bulbs are CFL in 2012.

The retrofit: average scenario models the potential impact of a national energy efficiency retrofit scheme aimed at the residential sector. We assume that 800,000 residential dwellings will be retrofitted between 2009 and 2020, in line with targets for the scheme [106]. As discussed in section 5.3.2.1 the retrofitting of existing dwellings was modelled as a simple shift in BER grade. Dwellings built to the latest BR are likely to achieve an A or B BER grade and are highly unlikely to undergo retrofit over the time horizon. Therefore we assume that only dwellings in the C to G BER bands will be retrofitted. We also assume that all dwellings in these bands are equally likely to undergo retrofit. For the retrofit: average scenario we assume improvements in BER corresponding to shallow retrofit measures, typical of those undertaken in previous government grant schemes i.e. roof and cavity wall insulation[103], as shown in Table 5.5.

Original BER	BER post shallow retrofit measures				
	One Storey Detached	Two Storey Detached	Two Storey Semi-Detached	Terraced	Apartment
C	C	C	C	C	C
D	D	C	C	C	C
E	D	D	D	D	D
F	E	E	E	E	E
G	F	F	E	F	G

Table 5.5: *BER improvement profile post shallow retrofit measures in the retrofit_average scenario*

5.3.4.3 Energy efficiency plus scenario

The energy efficiency+ scenario incorporates the measures from the energy efficiency scenario and explores the impact of a deep retrofitting scenario referred as retrofit: best, which supplants the retrofit: average scenario. For this scenario we assume that the same overall number of dwellings are retrofitted, again from the C-G BER bands, but in this case we assume the adoption of deeper retrofit measures, such as internal or external wall insulation, which have not been widely undertaken to date, resulting in the improvement profile shown in Table 5.6. The BER improvements shown may be not be possible to be achieved for all dwellings, this scenario can be considered to be an upper bound on the savings that could be achieved through a highly ambitious and successful residential retrofit programme. More detailed analysis on the potential for such deep retrofit measures is required, but this is left for further work.

Original BER	BER post deep retrofit measures				
	One Storey Detached	Two Storey Detached	Two Storey Semi-Detached	Terraced	Apartment
C	B	B	B	B	B
D	C	B	B	C	C
E	C	C	C	C	D
F	C	C	C	C	E
G	D	D	C	D	G

Table 5.6: *BER improvement profile post deep retrofit measures in the retrofit_best scenario*

5.4 Results

5.4.1 Summary of Overall Results

The results for overall TFC in 2020 for all sectors for each scenario, and for the residential sector in more detail, are shown in Table 5.3. For the reference scenario, all input data for the base year of 2008 is historical data and the energy demand is within 9% of the recorded energy balance by SEAI for 2008 [129]; for 2009 and 2010, the model's results are within 7% and 6% respectively [122]. The overall TFC in 2020 for the reference scenario is 15.3% higher than in 2008. The policies modelled in the energy efficiency scenario lead to an increase in TFC of 5.4% relative to base year energy consumption and the impact of the energy efficiency+ scenario is an increase of 2.5%; this equates to a decrease of 8.6% and 11.1% respectively with respect to the reference scenario.

Sector	Sub-Sector	Total Final Consumption; GWh			
		Base Year (2008)	Reference (2020)	Energy Efficiency (2020)	Energy Efficiency+ (2020)
Residential	Space Heating	23,481	23,062	19,818	17,352
	Water Heating	8,246	8,595	8,060	7,839
	Lighting	1,058	721	419	419
	Cooking	1,279	1,605	1,605	1,605
	Appliances	4,524	7,199	7,199	7,199
	Subtotal	38,588	41,182	37,100	34,402
Transport	All	46,229	55,243	45,985	44,752
Industry	All	29,273	37,867	37,867	37,867
Services	All	20,725	21,190	21,190	21,190
Total		134,803	155,481	142,142	138,223

Table 5.7: *TFC for all sectors and sub-sectors for base year and all scenarios*

5.4.2 Residential Sector Results

For the residential sector reference scenario TFC increases by 6.7%. This is despite the fact that due to obsolescence, 151,027 older, poorer performing dwellings have been abandoned and replaced with newly occupied dwellings built to the 2005 or 2008 BR, which are more efficient. Offsetting this however there is an overall increase in the numbers of dwellings from 1,560,416 in 2008 to 1,941,392 in 2020. One effect of the improvement in building regulations and the increased penetration of electric appliances is that by 2020, space and water heating TFC have decreased in share of total residential TFC from 82% to 73%, whereas lighting, cooking and appliances have increased in TFC from 18% to 27%.

For the energy efficiency scenario the combined impact of the policies discussed in section 5.3.4.2 on residential energy consumption is a reduction in TFC of 9.9% relative to the reference scenario. The result of the introduction of the 2011 and 2015BR was a reduction of 29% in the space and water heating requirement of all newly occupied dwellings from 2009 to 2020, in 2020. The retrofit_average scenario resulted in a 9% decrease in the space and water heating energy requirement of existing dwellings in 2020 relative to the reference scenario. Phasing out of incandescent light bulbs in favour of CFLs by 2012 leads to savings of 63% in 2012 relative to the reference, reducing to savings in 2020 of 42% due to the autonomous improvement assumed in the reference scenario. For the energy efficiency+ scenario, the retrofit_best scenario results in a reduction in the space and water heating energy demand of existing dwellings of 20% with respect to the reference scenario and 13% savings relative to the retrofit_average scenario.

5.5 Discussion

5.5.1 Residential sector

The Ireland LEAP model sought to provide a frame work for bringing together a number of sector specific energy demand models, involving a mix of bottom up and top down methodologies as appropriate for each case, into a single coherent model with an emphasis on the bottom up modelling of policy measures with a technical focus. For the residential sector this involved bringing together three strands of work:

- space & water heating in new dwellings
- space & water heating in existing & retrofitted dwellings
- lighting & appliances.

For the energy demand of space & water heating in new dwellings, including the effects of the introduction of the 2011 and 2015 BR, much of the modelling methodology had been devised prior to the development of the Ireland LEAP model and was subsequently implemented in LEAP [62]. For space & water heating in existing & retrofitted dwellings the work carried out for the Ireland LEAP model was the first step in the modelling process, and this lead on to more detailed analysis. For the modelling of the lighting and appliances subsector again a bottom up modelling approach was used. This allowed us to separate out the energy consumption of lighting, which is the only end-use within lighting & appliances for which a specific policy measure had been announced at the time of modelling. The bottom up disaggregated approach would also allow modelling of other specific energy efficiency measures in this area such as setting minimum energy ratings for white appliances. Unfortunately there are limitations to this approach, the first being the lack of recorded data for Ireland. For instance it was not possible to build a model of the stock of white appliances based on their energy ratings, as was done for existing dwellings for example, due to a lack of detailed data in this area. Secondly, the energy consumption of these appliances is highly dependent on their usage patterns, which are driven strongly by behavioural factors and electricity price signals. As such a combined bottom-up & top-down econometric model would improve modelling ability in this area. Developing such a model was outside the scope of the Ireland LEAP project and has been left for further work.

By combining the results for the three residential subsectors described above we can gain some further insights. The changing shares of energy consumption between space heating, water heating and lighting & appliances in each of the scenarios are shown in Table 5.8. Improvements in the insulation of the building envelope and in the efficiency of the space heating system lead to a significant drop in its share of total residential energy consumption. The energy demand of water heating is more difficult to reduce to such a degree. This is due to the fact that most of the energy used for hot water is embodied in the heated waste water, and can only be reduced through reduced demand for hot water or through heat recovery systems. In contrast to the energy demand for space and water heating , the energy consumption of lighting & appliances grows on a per dwelling per annum basis throughout the time period, leading to a doubling of its share of overall consumption. In this scenario, once the economical energy efficiency gains from the space heating subsector are realised it will be considerably more difficult to reduce the energy demand of the remaining two sectors through technical measures alone and further policies focused on occupant behaviour and energy sufficiency will be required.

Share of total consumption	Base year	Reference	Energy efficiency	Energy efficiency +
	2008	2020	2020	2020
space heating	61%	56%	53%	49%
water heating	21%	21%	22%	22%
lighting & appliances	18%	23%	25%	29%

Table 5.8: *Percentage share of energy demand of residential end-uses for each scenario*

5.5.2 Overall Ireland LEAP Model

Despite the range of energy models that have been developed to help guide and inform all aspects of energy policy [120] it has also been argued that, "such models provide biased estimates that tend to reinforce the status quo, inadequately inform policy-makers about new market potential, and serve to constrain the development of innovative policies" [130]. In this context, it is vital that energy models are able to bridge the "disconnect between the questions policy makers want answered and the results provided by modelling exercises" [131].

A number of caveats are associated with the results of the model:

- The inherent uncertainties in all future projections; this applies directly to fuel prices projections (IEA) and macro-economic projections of GDP, GNP & GVA [114].
- The actual results vary according to the model assumptions; this chapter uses macro-economic projections that underpinned the 2010 national energy forecasts [24] but Ireland's economic situation has worsened since then.
- Due to methodological differences, which were mostly due to data availability, some sectors are modelled in more detail and more robustly than others. This leads to results for certain sub-sectors having more uncertainty than other sub-sectors. It does however point to where resources should be targeted to improve the model.
- Like most energy systems modelling, the modelling here fails to account well for the behavioural aspect of energy consumers. This is a common problem for all energy models [132].
- For the energy efficiency policies under consideration, the level of success that will be achieved in implementing these policies is inherently uncertain and has a direct result on the overall level of energy savings achieved. A recent study by Rogan and O'Gallachoir of building regulations in Ireland for example has found discrepancies between the ex-ante targeted savings and the actual energy savings achieved from the introduction of the 2002 amendments to Part L of the building regulations [133]. The 2002 Building Regulations were designed to achieve a 20% reduction in dwelling energy consumption compared to the previous building regulations in place since 1997. The analysis by Rogan and O'Gallachoir used metered consumption data for gas connected dwellings to quantify the actual impact of the 2002 Building Regulations as compared to a control group of 1997 Building Regulation dwellings. The results focused on semi-detached dwellings in Dublin and found a substantial shortfall in the expected energy savings with a statistically significant reduction in energy consumption of 11.2±1.9 % compared to an ex-ante prediction of 20%. A separate analysis by Rogan and O'Gallachoir identified non-compliance with the building regulations as a key issue responsible for the observed shortfall in energy savings. Examining again a sample of gas connected semi-detached dwellings in Dublin built to

the 2002 regulations, they found the DEAP results were on average 13±1.6% greater than that required for compliance.

5.5.3 Practical aspects of modelling in LEAP

The bottom-up modelling approach adopted in this project for residential space & water heating energy demand resulted in a large, highly disaggregated set of archetypes which was data intensive to populate. The authors found this resulted in a highly branched tree structure within LEAP which, overall, was cumbersome to work with and inconvenient to adjust. The authors recommend that when implementing detailed bottom up models in LEAP, much of the detailed analysis should be carried out external to LEAP and the results imported. The internal tree structure for a given sector within LEAP should be simplified so far as possible and the number of final end use branches should not be excessive.

5.6 Conclusions

The Ireland LEAP project has demonstrated a model for Ireland which at the sector specific level enables detailed analysis of the impact of individual energy efficiency policies, which in turn can be combined into aggregated scenarios, representing portfolios of policies. This chapter has focused in detail on the residential sector and has used bottom-up modelling to help quantify the impact of energy efficiency policies in this sector. Combined with three other sectors of the economy (transport, industry and services), the overall Ireland LEAP model has presented three aggregated energy demand scenarios: a reference scenario, an energy efficiency scenario and an energy efficiency+ scenario. In addition to the examples shown here, there is ample scope for running further scenarios on many of the policies contained in the NEEAP. In terms of a coherent monitoring of energy policy that combines ex-ante and ex-post analysis, LEAP offers a useful framework and a practical tool for improved communication between modelling experts and policy makers.

Government energy policy in the residential sector has been largely focused on two areas, improved building regulations and the introduction of a National Energy Retrofit Programme. Although building regulations have improved significantly from 1992 to 2008 the results of the LEAP model show that there remains considerable scope for technical energy savings to be made through the introduction of further planned improvements in 2011 and 2013, with the combined effect of these measures in 2020 being a reduction of 29% in the space and water heating requirement of all newly occupied dwellings from 2009 to 2020. For these energy savings to be fully realised adequate enforcement of the new regulations will be key, as this is an area that is currently lacking and will only become more crucial as the standards become more stringent. The introduction of a National Retrofit Programme was modelled in a simple way based on an improvement in BER band for dwellings undergoing retrofit. Rather than being a detailed forecast of the savings that will be realised through such a scheme this work provides an estimate of the upper bound technical energy saving potential In order for government policy to effectively realise this savings potential two aspects will need to be addressed, the number of dwellings undergoing retrofit and the depth of retrofit works carried out. While specific targets for numbers of dwellings to be retrofitted have been outlined, the improvement required in the depth of retrofit works being carried out over and above the shallow measures that have been successfully incentivised in recent years, needs to be explicitly acknowledged by policy makers.

Lastly, as new dwellings become more space and water heating efficient, there is a changing share of end-use energy from dwelling heating to dwelling appliances; with appliances increasing in share from 18% in the reference year to 23% in 2020 in the reference scenario and 29% in the energy efficiency+ scenario. There will be a need for energy efficiency policies to address this changing structure of energy demand.

6 Conclusion

6.1 Review of aims and objectives of thesis

At the outset of this thesis the author set out two related research questions. The first was as follows: What is the energy savings potential in 2020 due to the introduction of the 2008 and 2010 revisions to the building regulations governing the conservation of fuel and energy in dwellings? Chapter 2 addressed this question by developing an archetype model of newly occupied dwellings and using it to estimate the energy savings potential of the improved regulations. The projected energy savings due to the introduction of 2008 and 2010 building regulations are 3,547 GWh, which broadly agree with projections given in the National Energy Efficiency Action Plan. The DEAP modelling has shown that as only limited savings can be made in the water heating end use, the new building regulations will require significant improvement in space heating efficiency.

The second research question asked was: What is the energy savings potential of an ambitious national scheme aiming to carry out energy efficiency retrofit works on up to 1 million existing dwellings? Chapter 3 presents a bottom up approach to modelling the energy demand from the space and water heating end uses of the 2011 stock of residential dwellings and a method for estimating the energy savings potential of various retrofit measures. Chapter 4 uses this modelling approach to estimate the technical energy savings potential in the Irish residential sector due to the introduction of the BEH scheme. In the year 2020, the estimated technical energy savings potential lies in the range of 1,713 GWh to 10,817 GWh. Based on recent uptake of grants and the uncertainty involved in moving from a grant based scheme to more market based mechanisms the author estimates that it is more likely to fall within the lower end of this range, i.e. between 2,000 and 4,000 GWh. If the target savings for the scheme of 5,200 GWh are to be achieved it will require close to 750,000 dwellings to be retrofitted. Although this is less than the number targeted for the scheme it is in fact highly ambitious and close to the upper bound of the number of dwellings available for retrofit. It will also require a significant shift towards deeper retrofit measures. Our sensitivity analysis has shown that rebound of 100% is possible for dwellings with poor initial energy ratings, and that for a 4 degree internal temperature rise post retrofit even the deepest retrofit measures will be more than offset. This level of direct rebound would not be expected across the full range of dwellings retrofitted, Sorrell et al suggest that direct rebound for residential energy efficiency measures should not generally exceed 30% [21]. This will reduce the effectiveness of residential retrofit as an energy efficiency and green house gas abatement strategy but the resultant reduction in fuel poverty will have health and other societal benefits. Based on the work presented in these two chapters the author estimates that although the target energy savings for the scheme of 5,200 GWh are technically feasible there is a high risk of them not being met.

A key challenge for policy makers will be to enact a policy framework that is successful in leveraging greater investment in deeper retrofit measures from participants, both home owners and energy supply companies. Government policy is to replace the current grant based support with a "Pay as You Save" scheme from 2014. Details on the proposed operation of this scheme are not yet available. Policy makers have an opportunity to take lessons from the similar, recently implemented, Green Deal scheme in the UK. The NESC[6] report identifies a number of key factors that will need to be addressed for any policy in this area to be successful, including the need to specifically target the rental property sector and the need to develop a multi pronged approach that tackles financial barriers, split incentives, knowledge gaps and occupant behaviour. The wide range of potential final energy savings identified in this work, along with the range of barriers that have prevented the realisation of economic energy savings in the past, and which will now need to be overcome in a short space of time, point to a high degree of uncertainty as to whether targets will be met.

6.2 Contribution of thesis

This thesis makes a number of contributions in the area of residential sector energy demand modelling. The main focus of the thesis is on modelling policy measures specific to the Irish residential sector, though the modelling methodology adopted is equally applicable to any EU member state.

- The work presented in Chapter 2 contributed an independent analysis of the energy savings potential of the 2008 and 2010 building regulations, which closely agreed with the official energy savings estimates.
- Chapter 3 makes a significant contribution by utilising an important, newly available dataset, the NAS database of BER results, to construct a bottom-up engineering archetype model. This

dataset is ideally suited for this approach and to our knowledge this thesis represents the first time it has been used for this purpose. The modelling methodology is also novel in that it sets up wall type construction as a key variable for characterising the stock of existing dwellings and for estimating the likely distribution of dwellings made obsolete and retrofitted in the time period.

- Chapter 4 analyses the “Better Energy: Homes” scheme which aims to retrofit almost 1 million residential dwellings between 2012 and 2020, with target energy savings for the scheme of 5,200 GWh. A key contribution made in this chapter is to highlight the highly ambitious nature of these targets, and to identify the reasons why they risk not being met.
- Chapter 5 presents the Ireland LEAP project which has contributed to the SEAI Energy Forecasts for Ireland to 2020 report and helped address the shortage of bottom up modelling at a national level.
- In addition to the above contributions specifically towards modelling the Irish residential sector, in chapter 3 the author notes the value of the Irish BER dataset and the fact that this data set has been collected as part of the residential EPC scheme in accordance with the ESD. As EPCs are mandatory for all dwellings sold or rented throughout the EU a number of EU states should have similar such valuable datasets available for analysis, though to our knowledge this thesis is the first to make use of it for the purpose of populating a national level bottom up engineering archetype model. Examples of EU member states which produce energy performance certificates based on kWh/m2/annum figures, the same format as are used in this model, include Austria, Belgium, Czech Republic, Finland, France, Germany and Luxembourg.

6.3 Further research

6.3.1 Continuation and development of work from this thesis

The work presented in this thesis consists of three main sections. The archetype model of new dwellings presented in chapter 2, the archetype model of existing dwellings presented in chapters 3 and 4 and finally the LEAP model of the residential sector presented in chapter 5. Of these 3 pieces of work the archetype model of existing dwellings is the most advanced, the one with the most scope for further development, the one which has the potential to answer the most pressing policy questions and be most useful to policy makers. This therefore should be the start point of further development of the work done in this thesis.

A significant limitation of the bottom-up analysis carried out thus far was the inability to compare the modelled energy demand against actual metered energy consumption, so as to calibrate the key assumptions and validate the results. This was due to lack of sufficient available data. A small data set of metered energy consumption for dwellings which had undergone retrofit under the HESS scheme was available to the SEAI and used in their cost benefit analysis of the scheme[77] but this data could not be made available to researchers outside of SEAI for legal reasons. SEAI do publish annual data on the national energy balance which includes high level data on the total energy consumption in the residential sector as a whole, split by fuel type [134].

As a rough sense check it is possible to compare the predicted energy consumption of residential space and water heating, lighting, pumps and fans in the year 2011 from the bottom up model to the actual total residential energy demand as per the national energy balance in 2011 minus the proportion of residential electricity use that is due to appliances, as per SEAI estimates. The un-calibrated bottom up model results are 64% higher than climate corrected energy balance for 2011 minus the estimated share of electricity use due to appliances, which strongly suggests that the default DEAP model used consistently over estimates household energy consumption. In the terminology used by Sunikka-Blank and Galvin [92] this corresponds to an average pre-bound effect of 39%, i.e. actual energy consumption is on average 39% below modelled. For their research comparing a bottom up model of the German residential sector to metered energy consumption Sunikka-Blank and Galvin found an average pre-bound of 30%, while they report that similar work carried out by Tighelaar and Menkveld also found an average pre-bound effect of 30% in their analysis of Dutch households while Cayre et al found average pre-bound of 40% in their analysis of French households.

There are likely to be many factors contributing to the overestimation of energy demand in the DEAP model, one of the key reasons is likely to be the relatively high internal temperatures and comfort levels assumed as default, with a living area temperature of 21degC during heating periods in all dwellings and a non living area temperature of 18degC. As a simplified attempt to better match the model results to the observed overall energy demand the bottom up model was re-run assuming lower internal temperatures across all dwellings. For assumed living area and non living area temperatures during heated periods of 18degC and 15degC respectively the model pre-bound was reduced to 22% and for 16degC and 13degC respectively pre-bound was on average 7%. Adjusting just one variable in this manner and making the same adjustment across all dwelling types regardless of BER or building type is very simplistic but serves as a very basic sense check on results and illustrates the essential role of using real world empirical data to calibrate the key model assumptions against. Rather than simply calculating an average pre-bound effect for the entire stock it is more useful to establish the average pre-bound for as many individual model archetypes as is possible. This allows the development of a curve describing the relationship between modelled and measured dwelling energy consumption for a range of dwellings efficiencies. Sunikka-Blank and Galvin describe two studies that have done this for Germany and Belgium, Figure 6.1 is taken from their work [92] and shows the relationship between the scale of the observed pre-bound effect and the modelled energy efficiency in kWh/m^2/annum for a study group of German households.

While it is possible to apply an adjustment factor to the results of a bottom up model to account for the observed difference between modelled and measured energy consumption as described above it would be more in keeping with the principles of bottom up modelling to instead use any improved data to modify the underlying model assumptions, for example internal temperature, but also other key variables such as heating hours, fraction of the dwelling that is considered living area, air changes per hour etc. An example of such calibration of bottom-up engineering type model assumptions and parameters is given by Booth et al [135].

As a logical next step to improve and further develop the bottom-up archetype model of existing dwellings developed in this thesis the author recommends the calibration of model assumptions, key input parameters and results against measured energy consumption for Ireland, using the work done in the above studies as a guide and tailoring the methodology to suit the dwelling stock characteristics and data availability specific to Ireland.

With regards to new dwellings, the modelling of new dwelling archetypes could be incorporated into the existing dwelling model, either by introducing new archetypes to account for new dwellings or else staying with the same 175 archetypes established to account for existing dwellings, which are already capable of accounting for new highly efficient dwellings. This would then give a complete bottom –up model of residential sector space and water heating energy demand.

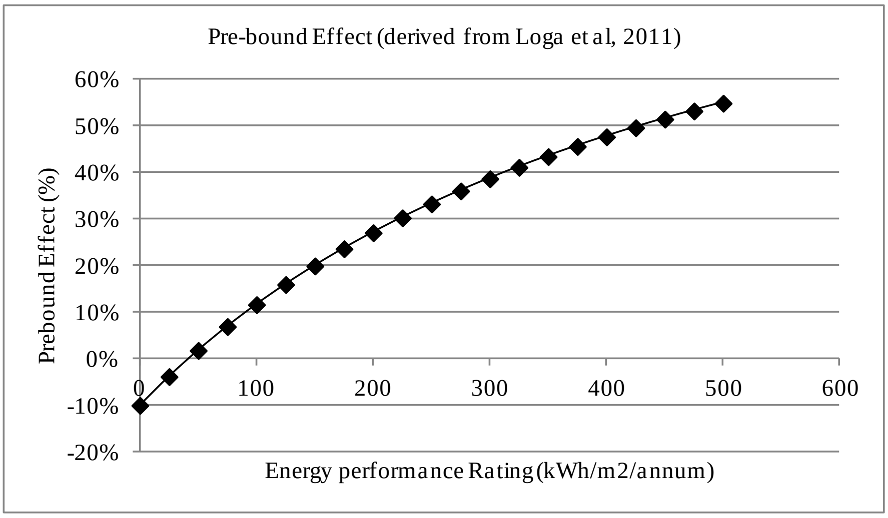

Figure 6.1: *Pre-bound versus energy performance rating as described in [92]*

6.3.2 Electrification of residential space heating as a green house gas abatement strategy

Further work is currently underway in the Energy Policy and Modelling Group in UCC on modelling the CO2 emissions that could be avoided by fuel switching from the oil central heating systems which are prevalent in much of rural Ireland to air source electric heat pump systems. This research will make further use of the NAS BER database and the bottom up archetype modelling approach to estimate the avoided CO_2 emissions from reduced oil consumption, while the corresponding increase in electricity demand and associated emissions will be modelled in detail through the Plexus software package.

6.3.3 Hybrid modelling

Purely bottom-up models such as that developed by the author in this thesis are valuable for establishing the baseline technical energy savings potential for specific policy measures. In order to accurately estimate the actual realised energy savings taking into account the complex interaction of occupants, dwellings, energy prices, changes to societies attitudes to energy and the environment etc the next generation of domestic energy models will require a hybrid modelling approach, which will involve the collaboration and cooperation of experts across a range of disciplines, including economists, social scientists and engineers[19]. For such a research project to be conducted in Ireland the vital first step will be to significantly improve the data available to on residential energy consumption.

6.3.4 Developing improved data sets

Bottom up modelling is a potentially powerful tool for informing policy but the quality of the models that can be constructed and predictions made depends strongly on the input data available. The use of the BER database in this thesis enabled analysis of the residential sector in Ireland on a level of detail and accuracy not possible before. However this is only a first step and far more needs to be done.

If the BER data set could be combined with metered data consumption then the resulting dataset, linking detailed dwelling construction characteristics with actual energy demand for a large national scale data set, this would be an excellent resource for improved energy modelling and informing of policy. This point highlights that there is significant potential for improving the data available for research simply by combining and granting access to existing datasets. The Homes Energy Efficiency Database (HEED) project in the UK provides an example of what can be achieved. HEED has drawn together data from approximately 60 datasets collected from approximately 20 organisations including energy suppliers, government funded schemes, energy efficiency surveys and retrofit installers detailing the physical characteristics, heating systems, insulation types and micro generation technologies across the UK residential sector. HEED currently contains information on over 13 million homes from England, Wales, Scotland and Northern Ireland accounting for approximately 50% of the total UK housing stock[136, 137]. The UK government has also collected annual gas and electricity metered data for dwellings from energy suppliers since 2004. Significantly the government has linked together the HEED and the metered energy data using the physical property addresses and made this valuable combined dataset available to researchers for analysis [137].

As well as making the best use of what data is already available the author also recommends that data collection on residential energy demand be extended beyond what is currently in place. SEAI acknowledges both the current shortage of data available for understanding residential energy use and the need to fill data gaps where they exist. They also point to the fact that the Energy Statistics Regulation EC no 1099/2008 requires member states to collect more detailed residential energy end use data including the energy consumption of households split by end use for main fuel types [138].

Summerfield & Lowe highlight the need for the re-invigoration of the role of empirical evidence as a key step in the future development of all building energy demand models and the development of public policy [139]. They highlight the current deficit in this area, using as an illustrative example the fact that "*there is scant published evidence anywhere for the distributions of U-values measured in-situ for various construction types representative of the building stock under varying conditions (environmental, age, etc.)*". As a way of further illustrating the level of cultural change that must be encouraged in the collection of empirical data on residential energy demand in order to adequately inform energy models and public policy, Summerfield et al have highlighted the difference in culture and approach to data collection between this field and within the health science community [140].

The author recommends that further data collection across a sufficiently wide statistically significant sample of dwellings on key factors influencing residential energy demand, particularly on internal temperatures and heating patterns, the presence of fuel poverty, the usage of appliances and the share of electricity used for residential space and water heating should be a policy priority for government. The author notes that a fresh opportunity may exist in the next phase of the Better Energy Homes scheme. As the next phase of the scheme will be a "Pay as you Save" model, it should require a detailed BER style assessment before and after retrofit, followed by a long term billing analysis post retrofit. This will allow detailed ex post analysis of the actual energy reduction experienced, the effectiveness of the retrofit measures carried out and a quantification of the direct rebound effects experienced. Data collected by energy supply companies under these schemes would ideally be made available to researchers on the level of individual anonymized dwellings.

6.4 Recommendations

6.4.1 Usefulness of model results for policy makers considering uncertainties

Summerfield et al note that "*policy-makers may express the wish to be provided with unqualified scientific evidence, e.g. a straightforward prediction of how much policy X will reduce energy demand compared with policy Y by 2020. But the contingent and emergent nature of future outcomes often makes it impossible to accede to such simple requests*"[139]. Throughout this thesis model results have been presented in the form of numerical values, for example potential energy savings of 3,547GWh for the introduction of 2008 and 2010 building regulations for new dwellings. As has been emphasised in each chapter these figures need to be understood in context of the many caveats and uncertainties associated with the quality of the input data, the many assumptions and simplifications that are necessarily made and the modelling approach adopted. A significant weakness common to nearly all bottom up models, including the ones developed by the author for this thesis, is the inability to capture the uncertainty or confidence intervals associated with the input data, and to carry this rigorously through the model to give an error bound or confidence interval for the results [17, 135]. Instead a combination of scenario analysis and sensitivity analysis has been used to investigate the range of results possible, and in both cases this range was found to be very large, for example with the range of plausible energy savings for the national retrofit programme aimed at existing dwellings under different scenarios estimated from 1,713 GWh and 10,817 GWh.

In the face of this uncertainty it is clear that no single figure for energy savings can be taken from the model as being a definitive or key result. Indeed, it is certain that taken in isolation all of the figures given for estimations of future energy savings will be proven to be inaccurate to some degree or another. This fact of energy modelling, and for that matter all efforts at predictive modelling of real world systems, is best summed up by Box when he noted that, "*Essentially, all models are wrong, but some are useful*"[23]. What is important to take from such modelling work then is not the raw figures, but instead the more general insights gained. A summary of the take home messages for policy makers from this thesis is provided below.

6.4.2 Key messages for policy makers

In summary, the author makes a number of key recommendations based on the work carried out in this thesis.

- If the new building regulations are to be fully effective then it is crucial to ensure that they are being complied with and, therefore, the authorities must provide increased monitoring, enforcement, and if necessary training and quality control.
- If the national retrofit programme is to achieve energy savings in excess of 5,000 GWh then it will be crucial to incentivise significantly deeper retrofit measures for existing dwellings than are currently being adopted. The Government's proposed Pay as You Save scheme may achieve this but it will be necessary to monitor the progress and success of the scheme so as to identify at an early stage any barriers that have not been sufficiently addressed and if necessary to introduce further policy measures to tackle these.
- Considering the importance of measures focused on the residential sector in Irish energy policy the author recommends the establishment of a research project with the aim of developing a hybrid residential energy demand model for Ireland. The project should have the wide range of multi-disciplinary expertise required. High quality input data will also be key and where necessary the project should have the resources to survey and collect data across a sufficiently wide, statistically significant sample of dwellings.
- Detailed analysis and modelling of the energy system is crucial for informed policy making and reliable, detailed data is the foundation for this. The author recommends that the authorities make it a policy priority to greatly increase the quality of data available for analysis of energy consumption and energy efficiency measures in the residential sector. The author recommends that better use be made out of existing data sets by making it possible to combine data on the physical characteristics of dwellings with their energy consumption data and that this data then be made available to researchers. The collection of data on residential energy consumption should be expanded through purposefully designed research projects targeting specific areas of data deficiency for example internal temperature. Overall a cultural change is required in the collection of data on energy demand in buildings and in the residential sector, where the

collection of data is seen as a critical, fundamental step of both formulating and continuously evaluating energy policy.

References

1. ODYSSEE. *Energy Efficiency Indicators in Europe*. Available from: http://www.odyssee-indicators.org/.
2. Howley, M., et al., *Energy in Ireland; Key Statistics 2012*. 2012, Energy Policy Statistical Support Unit, Sustainable Energy Authority of Ireland.
3. CSO. *Census Data*. 2012; Available from: http://www.cso.ie/census/.
4. Ball, M., *European Housing Review 2009*. 2009, RICS (Royal Institution of Chartered Surveyors).
5. Dol, K. and M. Haffner, *Housing Statistics in the European Union 2010*. 2010, OTB Research Institute for the Built Environment.
6. O'Donnell, R., et al., *Towards a New National Climate Policy: Interim Report of the NESC Secretariat*, NESC, Editor. 2012, National Economic & Social Council Secretariat
7. O'Leary, F., M. Howley, and B.P. Ó Gallachóir, *Energy in the Residential Sector 2008 Report*. 2008, Energy Policy Statistical Support Unit, Sustainable Energy Authority Ireland.
8. Walker, N., et al., *Energy Forecasts for Ireland to 2020; 2009 Report*, SEAI, Editor. 2009, Energy Modleling Group, Sustainable Energy Authority of Ireland
9. Weyant, J. and J. Hill, *The Costs of the KyotoProtocol: A Multi Model Evaluation*, s.i. The Energy Journal, Editor. 1999.
10. Canes, M.E., *Economic Modeling of Climate Change Policy*. 2002, International Council for Capital Formation.
11. Huntington, H.G., J.P. Weyant, and J.C. Editor-in-Chief:Â Â Cutler, *Modeling Energy Markets and Climate Change Policy*, in *Encyclopedia of Energy*. 2004, Elsevier: New York. p. 41-53.
12. Swan, L.G. and V.I. Ugursal, *Modeling of end-use energy consumption in the residential sector: A review of modeling techniques.* Renewable and Sustainable Energy Reviews, 2009. **13**(8): p. 1819-1835.
13. Hourcade, J.C., et al., *Hybrid modeling: New answers to old challenges.* The Energy Journal, 2006.
14. Cayre, E., et al., *There are people in the houses! How the results of purely technical analysis of residential energy consumption are misleading for energy policies* in *eceee 2011 summer study*. 2011: Belambra Presqu'île de Giens, France
15. Cayla, J.-M., N. Maizi, and C. Marchand, *The role of income in energy consumption behaviour: Evidence from French households data.* Energy Policy, 2011. **39**(12): p. 7874-7883.
16. Aydinalp-Koksal, M. and V.I. Ugursal, *Comparison of neural network, conditional demand analysis, and engineering approaches for modeling end-use energy consumption in the residential sector.* Applied Energy, 2008. **85**(4): p. 271-296.
17. Natarajan, S., J. Padget, and L. Elliott, *Modelling UK domestic energy and carbon emissions: an agent-based approach.* Energy and Buildings, 2011. **43**(10): p. 2602-2612.
18. Kelly, S., *Do homes that are more energy efficient consume less energy?: A structural equation model of the English residential sector.* Energy, 2011. **36**(9): p. 5610-5620.
19. Kavgic, M., et al., *A review of bottom-up building stock models for energy consumption in the residential sector.* Building and Environment, 2010. **45**(7): p. 1683-1697.
20. Greening, L., D.L. Greene, and C. Difiglio, *Energy efficiency and consumption - the rebound effect - a survey.* Energy Policy, 2000. **28**(2000): p. 389-401.
21. Sorrell, S., J. Dimitropoulos, and M. Sommerville, *Empirical estimates of the direct rebound effect: A review.* Energy Policy, 2009. **37**(4): p. 1356-1371.
22. Chitnis, M., et al., *Turning lights into flights: Estimating direct and indirect rebound effects for UK households.* Energy Policy, 2013. **55**(0): p. 234-250.
23. Box, G.E.P. and N.R. Draper, *Empirical model building and response surfaces*. Wiley series in probability and mathematical statistics, ed. Wiley. 1987.
24. Clancy, M., J. Scheer, and B.P. Ó'Gallachóirm, *Energy forecasts for Ireland to 2020; 2010 Report*, SEAI, Editor. 2010.
25. Rogan, F., et al., *LEAPs and Bounds - an Energy Demand and Constraint Optimised Model of the Irish Energy System.* Energy Efficiency, 2013. **In Press**.
26. European_Commission, *EU Energy and Transport in Figures - Statistical Pocketbook 2009*. 2009.
27. European_Commission, *2006 Action Plan for Energy Efficiency: Realising the Potential* E. Commission, Editor. 2006.

28. EU, *Directive 2006/32/EC*. 2006.
29. Hull, D., B.P. O'Gallachoir, and N. Walker, *Development of a modelling framework in response to new European energy-efficiency regulatory obligations: The Irish experience.* Energy Policy, 2009. **37**(12): p. 5363-5375.
30. Dennehy, E., B.P. O Gallachoir, and M. Howley, *Energy Efficiency in Ireland; 2009 Report*, S.E.A.o.I.E.P.S.S. Unit, Editor. 2009.
31. EU, *Directive 2006/32/EC Article 4(1)*. 2006.
32. EU, *Directive 2006/32/EC Article 14(2)*. 2006.
33. Department_of_Energy, *Maximising Ireland's Energy Efficiency; The National Energy Efficiency Action Plan 2009-2020*, Department_of_Energy, Editor. 2009.
34. European_Commission. *National Energy Efficiency Action Plans*. Available from: http://ec.europa.eu/energy/efficiency/end-use_en.htm.
35. Department_of_Energy, *Maximising Ireland's Energy Efficiency; The National Energy Efficiency Action Plan 2009-2020, Annex 02*, Department_of_Energy, Editor. 2009.
36. Farahbakhsh, H., V.I. Ugursal, and A.S. Fung, *A residential end use energy consumption model for Canada.* International Journal of Energy Research, 1998. **22**(13): p. 1133-43.
37. Aydinalp, M., V. Ismet Ugursal, and A.S. Fung, *Modeling of the space and domestic hot-water heating energy-consumption in the residential sector using neural networks.* Applied Energy, 2004. **79**(2): p. 159-178.
38. Aigner, D.J., C. Sorooshian, and P. Kerwin, *Conditional Demand Analysis for Estimating Residential End-Use Load Profiles.* The Energy Journal, 1984. **5**(3): p. 81-97.
39. *Review of the BERR Energy Demand Model*. 2008, Oxford Economics.
40. Shorrock, L.D. and J.E. Dunster, *The physically-based model BREHOMES and its use in deriving scenarios for the energy use and carbon dioxide emissions of the UK housing stock.* Energy Policy, 1997. **25**(12): p. 1027-1037.
41. SEAI. *Dwelling Energy Assessment Procedure*. 2012a; Available from: http://www.sei.ie/Your_Building/BER/BER_Assessors/Technical/DEAP/.
42. EU, *Directive 2002/91/EC of the European Parliament and of the Council of 16 Dec 2002 on the energy performance of buildings*, EU, Editor. 2002.
43. ISO, *ISO 13790:2008 Energy performance of buildings -- Calculation of energy use for space heating and cooling*, ISO, Editor. 2008.
44. DECC, *The Standard Assessment Procedure for Energy Rating of Dwellings*. 2005, UK Department of Energy and Climate Change.
45. Department_of_the_Environment, *Building Regulations 2005: Technical Guidance Document L; Conservation of Fuel and Energy*. 2005, Department of the Environment, Heritage and Local Government.
46. Department_of_the_Environment, *Building Regulations 2007; Technical Guidance Document L, Conservation of Fuel and Energy - Dwellings*. 2007, Department of Environment, Heritage and Local Government.
47. Department_of_the_Environment, *Building Regulations 2002: Technical Guidance Document L; Conservation of Fuel and Energy*. 2002, Department of the Environment, Heritage and Local Government.
48. SEAI. *DEAP Manual Version 3.2.1*. 2012d; Available from: http://www.seai.ie/Your_Building/EPBD/DEAP/.
49. Department_of_the_Environment, *Building Regulations 1997: Technical Guidance Document L; Conservation of Fuel and Energy*. 1997, Department of the Environment, Heritage and Local Government.
50. Department_of_the_Environment. *Housing Statistics Data*. 2012; Available from: http://www.environ.ie/en/Publications/StatisticsandRegularPublications/HousingStatistics/.
51. McCarthy, C., A. Hughes, and E. Woelger, *Where have all the houses gone?* 2003.
52. Barrett, A., I. Kearney, and J. Goggin, *Quarterly Economic Commentary Spring 2009. ESRI Research Bulletin 09/1.* 2009.
53. Hong, S.H., T. Oreszczyn, and I. Ridley, *The impact of energy efficient refurbishment on the space heating fuel consumption in English dwellings.* Energy and Buildings, 2006. **38**(10): p. 1171-1181.
54. Hong, S.H., et al., *A field study of thermal comfort in low-income dwellings in England before and after energy efficient refurbishment.* Building and Environment, 2009. **44**(6): p. 1228-1236.
55. Oreszczyn, T., et al., *Determinants of winter indoor temperatures in low income households in England.* Energy and Buildings, 2006. **38**(3): p. 245-252.

56. Greening, L.A. and D.L. Greene, *Energy use, technical efficiency, and the rebound effect: a review of the literature, Report to the US Department of Energy*. 1998.
57. Geller, H. and S. Attali, *The experience with energy efficiency policies and programmes in IEA countries - learning from the critics; IEA Information Paper*. 2005, IEA.
58. Berkhout, P.H.G., J.C. Muskens, and J. W. Velthuijsen, *Defining the rebound effect.* Energy Policy, 2000. **28**(2000): p. 425-432.
59. Utley, J. and L.D. Shorrock, *Domestic Energy Fact File 2006*. 2006, Building Research Establishment.
60. ADEME, *Evaluation of Energy Efficiency in the EU-15 - Indicators and Measures.* 2007.
61. Department_of_Communications, *Government White Paper: Delivering a sustainable energy future for Ireland*. 2007, Department of Communications, Marine and Natural Resources.
62. Dineen, D. and B.P. Ó'Gallachóir, *Modelling the impacts of building regulations and a property bubble on residential space and water heating.* Energy and Buildings, 2010. **43**(1): p. 166-178.
63. Daly, H., Dineen, D., Rogan, F., Cahill, C., *Bottom-Up Energy Demand Modelling - LEAP Ireland, Section 7 of Clancy M., Scheer J. and Ó Gallachóir B. P., 2010, Energy Forecasts in ireland to 2020; 2010 Report*. 2010, SEAI.
64. DCENR. *Better Energy; The National Upgrade Programme webpage*. 2012; Available from: http://www.dcenr.gov.ie/Energy/Energy+Efficiency+and+Affordability+Division/Better+Energy.htm.
65. Kannan, R. and N. Strachan, *Modelling the UK residential energy sector under long-term decarbonisation scenarios: Comparison between energy systems and sectoral modelling approaches.* Applied Energy, 2009. **86**(4): p. 416-428.
66. Mata, Ã.r., A.S. Kalagasidis, and F. Johnsson, *A modelling strategy for energy, carbon, and cost assessments of building stocks.* Energy and Buildings, 2013b. **56**(0): p. 100-108.
67. Mata, Ã.r., A. Sasic Kalagasidis, and F. Johnsson, *Energy usage and technical potential for energy saving measures in the Swedish residential building stock.* Energy Policy, 2013a(0).
68. Giraudet, L., C. Guivarch, and P. Quirion, *A model of the French residential demand for heating energy to evaluate the impact of policy instruments*, in *IEW workshop 2010*. 2010: Stockholm.
69. Clinch, J.P. and J.D. Healy, *Domestic energy efficiency in Ireland: correcting market failure.* Energy Policy, 2000a. **28**(1): p. 1-8.
70. Clinch, J.P. and J.D. Healy, *Cost-benefit analysis of domestic energy efficiency.* Energy Policy, 2000b. **29**(2): p. 113-124.
71. Clinch, J.P., J.D. Healy, and C.n. King, *Modelling improvements in domestic energy efficiency.* Environmental Modelling & Software, 2001. **16**(1): p. 87-106.
72. Healy, J.D. and J.P. Clinch, *Fuel poverty, thermal comfort and occupancy: results of a national household-survey in Ireland.* Applied Energy, 2002. **73**(2002): p. 329-343.
73. Clinch, J.P. and J.D. Healy, *Valuing improvements in comfort from domestic energy-efficiency retrofits using a trade-off simulation model.* Energy Economics, 2003. **25**(5): p. 565-583.
74. Healy, J.D. and J.P. Clinch, *Quantifying the severity of fuel poverty, its relationship with poor housing and reasons for non-investment in energy-saving measures in Ireland.* Energy Policy, 2004. **32**(2): p. 207-220.
75. Rogan, F. and B.P. O'Gallachoir, *Building Regulations - how effective are they at delivering energy efficiency?*, in *IN REVIEW*. 2013.
76. Ahern, C., P. Griffiths, and M. O'Flaherty, *State of the Irish housing stock ”Modelling the heat losses of Ireland's existing detached rural housing stock & estimating the benefit of thermal retrofit measures on this stock.* Energy Policy, 2013(0).
77. Scheer, J., M. Clancy, and S. Ni Hogain, *Quantification of energy savings from Ireland's Home Energy Saving scheme:an ex post biling analysis.* Energy Efficiency, 2012. **5**(1).
78. Leahy, E. and S. Lyons, *Energy use and appliance ownership in Ireland.* Energy Policy, 2010. **38**(8): p. 4265-4279.
79. Leahy, E., S. Lyons, and S. Walsh, *Electrical Appliance Ownership and Usage in ireland*. 2012, Economic and Social Research Institute.
80. O'Doherty, J., S. Lyons, and R.S.J. Tol, *Energy-using appliances and energy-saving features: Determinants of ownership in Ireland.* Applied Energy, 2008. **85**(7): p. 650-662.

81. Hyland, M., R.C. Lyons, and S. Lyons, *The value of domestic building energy efficiency - evidence from Ireland*, in *University of Oxford; Department of Economics Discussion Paper Series*. 2012.
82. Sartori, I., B.r.J. Wachenfeldt, and A.G. Hestnes, *Energy demand in the Norwegian building stock: Scenarios on potential reduction.* Energy Policy, 2009. **37**(5): p. 1614-1627.
83. SEAI. *Dwelling Energy Assessment Procedure (DEAP) 2006 EDITION, VERSION 2.2: Irish official method for calculating and rating the energy performance of dwellings* 2008; Available from: http://www.sei.ie/uploadedfiles/InfoCentre/BER/DEAP__Version_2.2_Manual_February_2008.pdf.
84. SEAI. *BER What is it?* 2012c; Available from: http://www.seai.ie/Your_Building/BER/BER_FAQ/FAQ_BER/General/BER_what_is_it_.html.
85. SEAI. *National BER Research Tool*. 2012b; Available from: http://www.seai.ie/Your_Building/BER/National_BER_Research_Tool/.
86. DoEHLG. *Housing Statistics Data*. Available from: http://www.environ.ie/en/Publications/StatisticsandRegularPublications/HousingStatistics/.
87. EU, *European Communities Energy Performance of Buildings Regulations*, in *S.I. No. 666 of 2006*. 2006, IRLGOV: Ireland.
88. SEAI, *Bringing Energy Home; Understanding how people think about energy in their homes.* 2010.
89. Curtin, J., *Greenprint; For a National Energy Efficiency Retrofit Programme*. 2009.
90. FitzGerald, J., *The Irish Housing Stock; Growth in the Number of Vacant Dwellings*, J. FitzGerald, Editor. 2005, Economic and Social Research Institute.
91. NSAI. *National Standards Authority of Ireland Window Energy Performance Certification Scheme*. 2012; Available from: http://www.nsai.ie/Our-Services/Certification/Agrement-Certification/WEP-(Wind-Energy-Performance)-Scheme.aspx.
92. Sunikka-Blank, M. and R. Galvin, *Introducing the prebound effect: the gap between performance and actual energy consumption*. 2012, Building Research and Information.
93. Baker, P., *Historic Scotland Technical paper 10; U-values and traditional buildings; In situ measurements and their comparisons to calculated values*. 2011, Glasgow Caledonian University.
94. Siller, T., M. Kost, and D. Imboden, *Long-term energy savings and greenhouse gas emission reductions in the Swiss residential sector.* Energy Policy, 2007. **35**(1): p. 529-539.
95. Johnston, D., R. Lowe, and M. Bell, *An exploration of the technical feasibility of achieving CO2 emission reductions in excess of 60% within the UK housing stock by the year 2050.* Energy Policy, 2005. **33**(13): p. 1643-1659.
96. McKinsey. *Greenhouse gas abatement cost curves*. Available from: http://www.mckinsey.com/clientservice/sustainability/Costcurves.asp.
97. Amstalden, R.W., et al., *Economic potential of energy-efficient retrofitting in the Swiss residential building sector: The effects of policy instruments and energy price expectations.* Energy Policy, 2007. **35**(3): p. 1819-1829.
98. Motherway, B., Walker N. And McKinsey and Co, *Ireland's Low-Carbon Opportunity. An analysis of the costs and benefits of reducing greenhouse gas emissions.*, SEAI, Editor. 2009, SEAI.
99. IEA, *World Energy Outlook 2012*. 2012: iea.
100. EU, *Directive 2012/27/EU on Energy Efficiency* 2012.
101. EU, *Directive 2010/31/EU on the Energy Performance of Buildings* 2010.
102. EnergyCommunity. 2012; Available from: http://www.energy-community.org/portal/page/portal/ENC_HOME/AREAS_OF_WORK/ENERGY_EFFICIENCY/NEEAPs.
103. SEAI. *Better Energy Statistics*. 2013; Available from: http://www.seai.ie/Grants/Better_energy_homes/Better_Energy_Statistics/.
104. Jim Scheer, M.C., Sadhbh Ni Hogain, *Quantification of energy savings from Ireland's Home Energy Saving scheme:an ex post biling analysis.* Energy Efficiency, 2012. **5**(1).
105. Department_of_Finance, *National Recovery Plan 2011-2014*, Department_of_Finance, Editor. 2011.
106. Department_of_Energy, *National Energy Retrofit Programme; Consultation Document.*, Department_of_Energy, Editor. 2010.

107. Joseph Curtin, J.M., *Thinking Deeper: Financing Options for Home Retrofit*. 2011, The Institute of International and European Affairs.
108. Clancy, M., J. Scheer, and B.P. Ó'Gallachóir, *Energy forecasts for Ireland for 2020; 2011 report*, SEAI, Editor. 2011.
109. Howells, M., et al., *OSeMOSYS: The Open Source Energy Modeling System: An introduction to its ethos, structure and development.* Energy Policy, 2011. **39**(10): p. 5850-5870.
110. Suganthi, L. and A.A. Samuel, *Energy models for demand forecastingâ€"A review.* Renewable and Sustainable Energy Reviews, 2011. **16**(2): p. 1223-1240.
111. Nakata, T., *Energy-economic models and the environment.* Progress in Energy and Combustion Science, 2004. **30**(4): p. 417-475.
112. Edenhofer, O., et al., *The economics of low stabilization: Model comparison of mitigation strategies and costs.* The Energy Journal, 2010. **31**: p. 11-48.
113. Barker, T., et al., *Contribution of Working Group III to the Fourth Assessment of the Intergovernmental Panel on Climate Change*, IPCC, Editor. 2007.
114. Bergin, A., et al., *Recovery scenarios for Ireland; An update*. 2010, ESRI.
115. Van Beeck, N., *Classification of Energy Models*. 1999, Tilburg University & Eindhoven University of Technology.
116. Heaps, C., *LEAP 2011 User Guide*. 2011: Stockholm Envrironmental Institute.
117. Loulou, R., et al. *Documentation for the TIMES model, Energy Technology Systems Analysis Programme (ETSAP)*. 2005; Available from: http://www.etsap.org/documentation.asp.
118. Loulou, R. and M. Labriet, *ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure.* Computational Management Science, 2007. **5(1-2)**: p. 7-40.
119. Messner, S. and M. Strubbegger. *User's guide for MESSAGE III, WP-95-69*. 1995; Available from: http://webarchive.iiasa.ac.at/Research/ENE/model/message.html.
120. Connolly, D., et al., *A review of computer tools for analysing the integration of renewable energy into various energy systems.* Applied Energy, 2010. **87**(4): p. 1059-1082.
121. Dagher, L. and I. Ruble, *Modeling Lebanon's electricity sector: Alternative scenarios and their implications.* Energy, 2011. **36**(7): p. 4315-4326.
122. Howley, M., E. Dennehy, and B.P. O'Gallachoir, *Energy in Ireland 1990-2009*. 2010, Energy Policy Statistical Support Unit, Sustainable Energy Authority of Ireland.
123. Shin, H.-C., et al., *Environmental and economic assessment of landfill gas electricity generation in Korea using LEAP model.* Energy Policy, 2005. **33**(10): p. 1261-1270.
124. Takase, K. and T. Suzuki, *The Japanese energy sector: Current situation, and future paths.* Energy Policy. **39**(11): p. 6731-6744.
125. Breslow, M. and M. Affairs, *Massachusetts Clean Energy and Climate Plan for 2020.* 2011. p. 1-136.
126. Mundaca, L., et al., *Evaluating Energy Efficiency Policies with Energy-Economy Models.* Annual Reviews of Environment and Resources, 2010: p. 1-42.
127. Welsch, M., et al., *Modelling elements of Smart Grids â€" Enhancing the OSeMOSYS (Open Source Energy Modelling System) code.* Energy, 2012. **46**(1): p. 337-350.
128. Department_of_the_Environment. *National Survey of Housing Quality 2001/2002*. 2002; Available from: http://www.ucd.ie/issda/data/economicandsocialresearchinstituteesri/irishnationalsurveyofhousingquality/.
129. Howley, M., E. Dennehy, and B.P. O'Gallachoir, *Energy in Ireland 1990-2008*. 2009, Energy Policy Statistical Support Unit, Sustainable Energy Authority of Ireland.
130. Laitner, J.A.S., *Improving the Contribution of Economic Models in Evaluating Energy and Climate Change Mitigation Policies.* 2006, aceee.
131. Munson, D., *Predicting Energy Futures.* The Electricity Journal, 2004. **17**(3): p. 70-79.
132. Laitner, J.A.S., et al. *Room for Improvement: Increasing the Value of Energy Modelling for Policy Analysis*. in *Proceedings of aceee, June 27 2002*. 2002.
133. Rogan, F. and B.P. Ó Gallachóir. *Ex-post evaluation of a residential energy efficiency policy measure using empirical data*. in *eceee*. 2011. Belambra Presqu'ile de Giens, France.
134. SEAI. *Statics Publications; Energy balance*. 2013; Available from: http://www.seai.ie/Publications/Statistics_Publications/Energy_Balance/.
135. Booth, A.T., R. Choudhary, and D.J. Spiegelhalter, *Handling uncertainty in housing stock models.* Building and Environment, 2011. **48**(0): p. 35-47.
136. Energy_saving_trust. *Homes Energy Efficiency Database*. 2013 [cited 2013; Available from: http://www.energysavingtrust.org.uk/Organisations/Government-and-local-programmes/Programmes-we-deliver/Homes-Energy-Efficiency-Database.

137. Hamilton, I.G., et al., *Energy efficiency in the British housing stock: Energy demand and the Homes Energy Efficiency Database*. 2013. p. 462-480.

138. Dennehy, E. and M. Howley, *Energy in the Residential Sector; 2013 Report*, S.E.A.o. Ireland, Editor. 2013.

139. Summerfield, A.J. and R. Lowe, *Challenges and future directions for energy and buildings research.* Building Research & Information, 2012. **40:4**: p. 391-400.

140. Summerfield, A., et al. *How useful are building energy models for policy? A UK perspective*. in *12th conference of international building performance simulation association*. 2011. Sydney.

Appendix A: Tabulated data in support of Figures through-out thesis.

This section contains the tabulated data for all graphs within the thesis. Each table presented here is given the Figure number and name of the relevant graph in the thesis.

Year	Total House Completions
1970	13,887
1971	15,380
1972	21,572
1973	24,660
1974	26,256
1975	26,892
1976	24,000
1977	24,548
1978	25,444
1979	26,544
1980	27,785
1981	28,917
1982	26,798
1983	26,138
1984	24,944
1985	23,948
1986	22,680
1987	18,450
1988	15,654
1989	18,068
1990	19,539
1991	19,652
1992	22,464
1993	21,391
1994	26,863
1995	30,575
1996	33,725
1997	38,842
1998	42,349
1999	46,512
2000	49,812
2001	52,602
2002	57,695
2003	68,819
2004	76,954
2005	80,957
2006	93,419
2007	78,027
2008	51,724
2009	26,420
2010	14,602
2011	10,480
2012	8,488

Figure 1.1: Number of dwellings constructed per annum

Period Built	Before 1919	1919-1945	1946-1960	1961-1970	1971-1980	1981-1990	1991-2000	2001-2005	2006 or later	Not stated
Number in 2011 stock	149,939	114,817	127,691	114,510	214,197	172,413	238,724	266,110	171,397	79,610

Figure 1.2: Age profile of dwellings in 2011

Floor area m^2	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Houses	149	144	148	148	149	159	164	168	176	192	190	207
Multi development houses	131	120	119	119	125	128	133	133	133	136	135	142
One off houses	186	192	199	205	214	224	238	248	253	250	249	248
Apartments	78	78	80	77	78	81	85	85	93	91	103	90

Figure 1.3: Average floor area of dwellings applying for planning permission

Number of dwellings:		Oil	Natural Gas	Solid Fuels	Electricity	All Other
Aggregate Rural Area	Detached House	353,298	6,302	103,931	10,284	21,611
	Semi-detached House	40,200	3,714	14,790	2,403	2,401
	Terraced House	12,900	1,894	5,974	1,777	1,405
	Apartment	3,264	1,011	872	3,375	641
Aggregate Town Area	Detached House	107,227	75,413	10,269	6,517	5,017
	Semi-detached House	131,355	222,535	19,623	12,619	7,011
	Terraced House	51,649	159,559	19,945	18,145	8,577
	Apartment	7,114	74,739	1,680	83,111	7,475

Figure 1.4: 2011 Residential dwelling stock split by building type and fuel type

Results of DEAP model of Energy Consumption						
	Space Heating		Water Heating		Pumps & Fans	Lighting
	Main	Secondary	Main	Secondary		
1 Story Detached	94.0	29.0	19.4	7.1	1.4	4.5
2 Story Detached	72.3	22.3	19.4	7.1	1.4	4.5
2 Story Semi Detached	65.8	20.4	19.4	7.1	1.4	4.5
2 Story Terraced	59.3	18.3	19.4	7.1	1.4	4.6
Apartment	40.5	0.0	18.8	6.9	1.4	5.3

Figure 2.1: Results of DEAP model of Energy Consumption

Energy Consumption per m2 of under Different Regulations, by Energy End Use							
		Space Heating		Water Heating		Pumps & Fans	Lighting
		Main	Secondary	Main	Secondary		
One Story Detached House	2005 Building Regulation	94.0	29.0	19.4	7.1	1.4	4.5
	2008 Building Regulation	54.9	16.9	13.0	4.8	1.4	2.2
	2010 Building Regulation	34.5	10.6	9.8	3.6	1.4	2.2
Apartment	2005 Building Regulation	40.5	0.0	18.8	6.9	1.4	5.3
	2008 Building Regulation	21.5	0.0	13.3	4.9	1.4	2.6
	2010 Building Regulation	10.7	0.0	10.5	3.9	1.4	2.6

Figure 2.2: End Use Energy Consumption of One Story Detached House and Apartment under Different Building Regulations

Annual Dwellings Newly Occupied			
Year	Detached house	Scheme House	Total Flat
1994	10,524	10,804	5,112
1995	12,210	11,953	6,009
1996	15,228	11,423	6,670
1997	17,003	14,137	7,302
1998	16,974	15,837	9,137
1999	21,183	15,733	9,196
2000	23,898	16,628	8,886
2001	24,500	17,076	10,626
2002	22,027	23,630	11,638
2003	22,210	31,370	14,839
2004	20,181	40,267	16,106
2005	20,362	42,160	18,035
2006	22,806	50,267	19,946
2007	19,663	39,273	18,691
2008	11,126	13,953	7,975
2009	4,287	6,810	6,403
2010	3,145	5,646	6,209
2011	4,840	7,507	6,808
2012	6,500	9,356	7,456
2013	7,811	11,078	8,579
2014	9,401	12,901	9,320
2015	10,956	14,712	10,111
2016	11,103	15,004	10,468
2017	11,242	15,294	10,833
2018	11,376	15,581	11,208
2019	11,503	15,866	11,590
2020	11,624	16,149	11,982

Figure 2.3: Projected numbers of new dwellings completed.

Year	Annual Dwellings Newly Occupied	Annual dwellings Newly Built
1994	26,772	26,440
1995	26,911	30,172
1996	27,050	33,321
1997	35,580	38,442
1998	35,780	41,948
1999	35,980	46,112
2000	36,181	49,412
2001	36,381	52,202
2002	36,581	57,295
2003	55,011	68,419
2004	55,344	76,554
2005	55,678	80,557
2006	56,011	93,019
2007	55,826	77,627
2008	45,476	33,054
2009	24,077	17,500
2010	20,637	15,000
2011	26,355	19,156
2012	32,073	23,312
2013	34,546	27,467
2014	39,773	31,623
2015	45,000	35,779
2016	46,000	36,574
2017	47,000	37,369
2018	48,000	38,164
2019	49,000	38,959
2020	50,000	39,755

Figure 2.4: Projected numbers of newly built and newly occupied dwellings

Year	2002/05 Building Regulations	2008 Building Regulations	2010 Building Regulations	Total
2005	55,678	0	0	55,678
2006	56,011	0	0	56,011
2007	55,826	0	0	55,826
2008	37,213	8,264	0	45,476
2009	10,952	13,125	0	24,077
2010	5,637	11,250	3,750	20,637
2011	7,199	4,789	14,367	26,355
2012	8,761	0	23,312	32,073
2013	7,079	0	27,467	34,546
2014	8,150	0	31,623	39,773
2015	9,221	0	35,779	45,000
2016	9,426	0	36,574	46,000
2017	9,631	0	37,369	47,000
2018	9,836	0	38,164	48,000
2019	10,041	0	38,959	49,000
2020	10,245	0	39,755	50,000

Figure 2.5: Projected numbers of dwellings built to different building regulations

Year	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Total Stock	17,842	18,697	17,829	17,195	17,270	17,099	17,317	17,294	17,616	17,054
Post 1997 Newly Built Dewllings		18,572	18,273	18,320	18,426	16,929	16,544	15,022	13,134	13,590
Post 1997 Cumulative New Stock		18,572	18,422	18,388	18,397	18,100	17,737	17,221	16,565	16,152
1997 Existing Stock	17,842	18,701	17,791	17,080	17,123	16,934	17,226	17,314	17,956	17,397

Figure 2.6:Space heating consumption of pre and post 1995 stock of occupied dwellings between 1995 and 2006

Year	kWh/dwelling/annum	
1990	Historical Data	1,499
1991		1,633
1992		1,780
1993		1,768
1994		1,839
1995		1,821
1996		1,954
1997		1,844
1998		1,811
1999		2,003
2000		2,108
2001		2,488
2002		2,456
2003		2,596
2004		2,733
2005		2,700
2006		2,907
2007	Future Projection	3,014
2008		3,103
2009		3,177
2010		3,239
2011		3,290
2012		3,333
2013		3,369
2014		3,399
2015		3,424
2016		3,445
2017		3,462
2018		3,476
2019		3,488
2020		3,498

Figure 2.7: Energy Consumption of Lighting and Appliances

Consumption/Newly Built Dw (MWh/annum)				
Year	Space Heating	Water Heating	Lighting & Appliances	Cooking
1997	18.47	3.94	1.84	0.83
1998	18.58	3.95	1.81	0.83
1999	18.28	3.94	2.00	0.83
2000	18.32	3.97	2.11	0.83
2001	18.43	4.01	2.49	0.83
2002	16.93	3.95	2.46	0.83
2003	16.55	4.04	2.60	0.83
2004	15.02	4.03	2.73	0.83
2005	13.14	3.96	2.70	0.83
2006	13.59	4.09	2.91	0.83
2007	13.24	4.02	3.01	0.83
2008	11.41	3.63	2.99	0.83
2009	8.31	3.06	3.10	0.83
2010	6.59	2.71	3.18	0.83
2011	6.17	2.56	3.24	0.83
2012	5.96	2.50	3.29	0.83
2013	5.55	2.41	3.34	0.83
2014	5.69	2.44	3.38	0.83
2015	5.79	2.46	3.41	0.83
2016	5.79	2.47	3.43	0.83
2017	5.79	2.48	3.45	0.83
2018	5.79	2.50	3.47	0.83
2019	5.80	2.51	3.48	0.83
2020	5.79	2.52	3.49	0.83

Figure 2.8: Energy Consumption of Average Newly Built Dwelling 1997-2020

Overall Residential Energy Demand, TWh			
Year	Baseline	2008 & 2010 Building Regulations	Building Regulations & Retrofitting of 2006 stock
2002	31.05	31.05	31.05
2003	32.79	32.79	32.79
2004	34.12	34.12	34.12
2005	35.74	35.74	35.74
2006	36.22	36.22	36.22
2007	37.28	37.28	37.14
2008	38.05	38.00	37.71
2009	38.32	38.19	37.77
2010	38.50	38.27	37.71
2011	38.79	38.39	37.71
2012	39.19	38.57	37.75
2013	39.63	38.74	37.80
2014	40.18	38.97	37.91
2015	40.84	39.26	38.08
2016	41.50	39.56	38.26
2017	42.18	39.85	38.44
2018	42.88	40.15	38.63
2019	43.59	40.46	38.83
2020	44.31	40.76	39.04

Figure 2.9: Residential Energy Demand Under Different Policy Scenarios

Residential sector energy demand TWh			
Year	Bottom up model of new dwellings 1997-2006, 1996 stock constant	Bottom up model of new dwellings 1997-2006, improvements within 1996 stock	Historicaly observed data, climate corrected
1990	26.50	26.50	26.50
1991	26.41	26.41	26.41
1992	24.58	24.58	24.58
1993	24.71	24.71	24.71
1994	25.20	25.20	25.20
1995	26.70	26.70	26.70
1996	26.39	26.39	26.39
1997	26.97	26.86	27.56
1998	27.64	27.42	29.39
1999	28.55	28.22	29.43
2000	29.37	28.94	29.39
2001	30.50	29.97	30.69
2002	31.13	30.50	31.05
2003	32.37	31.64	32.79
2004	33.53	32.71	34.12
2005	34.40	33.49	35.74
2006	35.56	34.56	36.22

Figure 2.10: Comparison of Bottom Up Model to Historical data 1997 - 2006

Residential energy demand, TWh				
Year	Baseline	Building Regulations & Retrofitting of 2006 stock	Top-down National Forecast Baseline	Top-down National Forecast White Paper
2002	31.05	31.05	31.05	31.05
2003	32.79	32.79	32.79	32.79
2004	34.12	34.12	34.12	34.12
2005	35.74	35.74	35.74	35.74
2006	36.22	36.22	36.22	36.22
2007	37.28	37.14	35.39	35.39
2008	38.05	37.71	35.95	35.60
2009	38.32	37.77	36.96	36.26
2010	38.50	37.71	37.68	36.63
2011	38.79	37.71	38.03	36.10
2012	39.19	37.75	38.55	35.75
2013	39.63	37.80	39.42	35.76
2014	40.18	37.91	40.36	35.82
2015	40.84	38.08	41.37	35.96
2016	41.50	38.26	42.38	36.10
2017	42.18	38.44	43.35	36.09
2018	42.88	38.63	44.28	36.04
2019	43.59	38.83	45.17	35.95
2020	44.31	39.04	46.04	35.83

Figure 2.10: Comparison of Bottom Up Model to Historical data 1997 - 2006

Dwelling type	% in NAS database
2St. SemiDet.	29.4%
1St. Apartment	21.0%
2St. Detached	13.8%
2St. Terraced	12.1%
1St. Detached	11.0%
1St. SemiDet.	3.5%
2St. Apartment	3.2%
3St.. SemiDet.	2.1%
3St. Terraced	1.5%
1St. Terraced	1.0%
3St. Detached	0.9%
Other	0.6%

Figure 3.1: Building types in NAS database

Wall type	U Value range		
	U </=0.6	0.6<U≤1.78	U >1.78
Blank	1.9%	4.4%	3.4%
Other	5.4%	3.1%	0.3%
225mm Solid brick	1.7%	3.9%	9.5%
325mm Solid Brick	1.0%	11.1%	0.4%
Stone	5.6%	21.8%	48.9%
Concrete Hollow Block	4.3%	8.2%	18.6%
Timber Frame	7.1%	1.6%	0.1%
Solid Mass Concrete	3.3%	7.1%	16.7%
300mm Cavity	42.0%	37.4%	2.0%
300mm Filled Cavity	27.8%	1.3%	0.0%

Figure 3.2: Wall construction type by U-value band according to NAS database

	pre 1919	1919-1945	1946-1960	1961-1970	1971-1980	1981-1990	1991-2000	2001-2005	2006-2011
Detached house	5%	7%	8%	9%	9%	10%	12%	9%	8%
Semi- detached house	16%	18%	17%	14%	15%	19%	22%	19%	30%
Terraced house	12%	14%	11%	10%	11%	12%	17%	13%	24%
Apartment	16%	18%	14%	16%	23%	28%	39%	37%	52%

Figure 3.3: Percent sample of the CSO figure represented in the NAS database.

Shares by Age-group in NAS & CSO										
		pre 1919	1919-1945	1946-1960	1961-1970	1971-1980	1981-1990	1991-2000	2001-2005	2006-2011
NAS	Number	13,647	14,174	15,663	13,591	26,848	25,270	48,139	50,811	45,718
	% of total	5%	6%	6%	5%	11%	10%	19%	20%	18%
CSO & Model	Number	150,053	118,147	133,126	120,567	226,501	182,245	253,864	283,085	181,820
	% of total	9%	7%	8%	7%	14%	11%	15%	17%	11%

Shares by Age-group in NAS & CSO										
		pre 1919	1919-1945	1946-1960	1961-1970	1971-1980	1981-1990	1991-2000	2001-2005	2006-2011
NAS	Number	13,647	14,174	15,663	13,591	26,848	25,270	48,139	50,811	45,718
	% of total	5%	6%	6%	5%	11%	10%	19%	20%	18%
CSO & Model	Number	150,053	118,147	133,126	120,567	226,501	182,245	253,864	283,085	181,820
	% of total	9%	7%	8%	7%	14%	11%	15%	17%	11%

Shares by BER Level								
		A	B	C	D	E	F	G
NAS & Model	Number	4,449	171,610	593,813	429,714	212,669	98,597	138,555
	% of total	0%	10%	36%	26%	13%	6%	8%

Shares by Wall Type						
		Un Insulated Solid Wall	Un Insulated Cavity Wall	Partially Insulated Solid Wall	Insulated Wall	Highly Insulated Wall
NAS & Model	Number	175,776	112,229	168,344	472,030	721,027
	% of total	11%	7%	10%	29%	44%

Figure 3.4: Shares of dwellings by Building Type, Age Group, BER and Wall Type in both the NAS and CSO databases.

Partially Insulated Solid: Boiler efficiency (%)		
Dwelling Type	Unaltered dwelling	After high efficiency boiler upgrade
C 1StDetached	91%	92%
C 2StDetached	89%	92%
C 2StSemiDet	90%	92%
C 2StTerraced	88%	92%
C 1StApartment	81%	92%
F 1StDetached	75%	92%
F 2StDetached	73%	92%
F 2StSemiDet	74%	92%
F 2StTerraced	75%	92%
F 1StApartment	100%	100%

Insulated Wall: Roof U-value (W/m^2K)		
Dwelling Type	Unaltered dwelling	After roof insulation upgrade
C 1StDetached	0.23	0.13
C 2StDetached	0.30	0.13
C 2StSemiDet	0.28	0.13
C 2StTerraced	0.28	0.13
C 1StApartment	0.14	0.14
F 1StDetached	0.45	0.13
F 2StDetached	0.40	0.13
F 2StSemiDet	0.38	0.13
F 2StTerraced	0.42	0.13
F 1StApartment	0.15	0.15

Insualted Wall: Window U-value (W/m^2K)		
Dwelling Type	Unaltered dwelling	After high performance windows upgrade
C 1StDetached	2.75	1.30
C 2StDetached	2.72	1.30
C 2StSemiDet	2.70	1.30
C 2StTerraced	2.78	1.30
C 1StApartment	2.56	1.30
F 1StDetached	3.59	1.30
F 2StDetached	3.06	1.30
F 2StSemiDet	3.02	1.30
F 2StTerraced	3.31	1.30
F 1StApartment	2.96	1.30

Un-Insulated Cavity Wall: Wall U-value (W/m^2K)		
Dwelling Type	Unaltered dwelling	After cavity wall insulation upgrade
C 1StDetached	0.95	0.33
C 2StDetached	1.03	0.33
C 2StSemiDet	1.07	0.33
C 2StTerraced	1.15	0.33
C 1StApartment	0.98	0.33
F 1StDetached	1.39	0.33
F 2StDetached	1.49	0.33
F 2StSemiDet	1.57	0.33
F 2StTerraced	1.56	0.33
F 1StApartment	1.00	0.33

Un-Insualted Solid Wall: Wall U-value (W/m^2K)		
Dwelling Type	Unaltered dwelling	After solid wall insulation upgrade
C 1StDetached		
C 2StDetached	2.04	0.27
C 2StSemiDet	2.03	0.27
C 2StTerraced	2.02	0.27
C 1StApartment	1.87	0.27
F 1StDetached	2.04	0.27
F 2StDetached	2.07	0.27
F 2StSemiDet	2.09	0.27
F 2StTerraced	2.07	0.27
F 1StApartment	2.06	0.27

Figure 3.5: Retrofit improvement profiles

Roof insulation				Solid wall insulation			
	UISW	UICW/PISW	IW		UISW	PISW	IW
C 1StDetached	0.0	5.0	6.3	C 1StDetached	0.0	27.4	12.7
C 2StDetached	9.1	7.5	7.0	C 2StDetached	63.7	39.0	17.4
C 2StSemiDet	9.8	6.2	5.8	C 2StSemiDet	66.3	38.7	17.0
C 2StTerraced	4.6	5.4	6.0	C 2StTerraced	53.8	34.3	11.8
C 1StApartment				C 1StApartment	62.9	33.7	12.1
F 1StDetached	23.2	28.4	26.6	F 1StDetached	111.6	75.8	23.3
F 2StDetached	27.7	32.2	24.6	F 2StDetached	134.7	102.8	48.5
F 2StSemiDet	27.4	35.2	20.8	F 2StSemiDet	124.1	95.3	48.0
F 2StTerraced	47.7	50.7	26.3	F 2StTerraced	92.4	72.5	34.5
F 1StApartment				F 1StApartment	126.8	102.3	37.8
Cavity wall insulation				Boiler & heating controls upgrade			
		UICW			UISW	UICW/PISW	IW
C 1StDetached		24.9		C 1StDetached	0.0	1.1	5.3
C 2StDetached		35.8		C 2StDetached	0.0	4.7	16.1
C 2StSemiDet		35.7		C 2StSemiDet	4.4	3.5	18.4
C 2StTerraced		31.9		C 2StTerraced	3.4	5.9	20.0
C 1StApartment		30.8		C 1StApartment	14.2	27.8	25.0
F 1StDetached		71.5		F 1StDetached	49.8	62.9	75.8
F 2StDetached		97.4		F 2StDetached	57.2	70.3	0.0
F 2StSemiDet		90.6		F 2StSemiDet	66.9	68.0	0.0
F 2StTerraced		69.0		F 2StTerraced	62.7	62.0	0.0
F 1StApartment		93.9		F 1StApartment	55.1	0.0	0.0
Solar water heating				High performance windows			
	UISW	UICW/PISW	IW		UISW	UICW/PISW	IW
C 1StDetached	0.0	14.4	21.6	C 1StDetached	0.0	3.6	4.5
C 2StDetached	11.5	13.2	21.6	C 2StDetached	2.7	3.7	4.7
C 2StSemiDet	18.9	15.8	27.2	C 2StSemiDet	8.9	3.8	4.7
C 2StTerraced	17.1	17.5	30.7	C 2StTerraced	3.6	5.0	6.6
C 1StApartment	0.0	0.0	0.0	C 1StApartment	7.1	9.4	6.0
F 1StDetached	39.5	42.0	64.5	F 1StDetached	7.5	9.8	15.5
F 2StDetached	32.9	36.6	40.8	F 2StDetached	9.1	8.8	24.4
F 2StSemiDet	42.0	45.9	48.9	F 2StSemiDet	12.7	12.1	20.5
F 2StTerraced	48.0	56.1	52.8	F 2StTerraced	13.3	13.1	26.1
F 1StApartment	0.0	0.0	0.0	F 1StApartment	7.1	15.0	20.1

Figure 3.6: Primary Energy Savings after the application of particular retrofit measures on sample dwellings.

Energy Savings kWh/m²/annum	Un-Insulated Cavity Wall Dwellings with Cavity Wall Insulation		Insulated Wall Dwellings with Solar Water Heating	
	Primary Energy	Delivered Energy	Primary Energy	Delivered Energy
C 1StDetached	24.9	22.7	21.6	20.4
C 2StDetached	35.8	32.5	21.6	20.2
C 2StSemiDet	35.7	32.5	27.2	25.8
C 2StTerraced	31.9	29.0	30.7	29.2
C 1StApartment	30.8	30.2	0.0	0.0
F 1StDetached	71.5	65.0	64.5	38.3
F 2StDetached	97.4	88.5	40.8	14.8
F 2StSemiDet	90.6	82.4	48.9	17.7
F 2StTerraced	69.0	62.7	52.8	19.1
F 1StApartment	93.9	34.8	0.0	0.0

Figure 3.7: Comparison of delivered energy and primary energy savings for sample measures and dwelling archetypes.

	Low temp	Mid temp	High temp
C 1StDetached	-32%	-16%	17%
C 2StDetached	-33%	-17%	18%
C 2StSemiDet	-32%	-17%	17%
C 2StTerraced	-30%	-16%	17%
C 1StApartment	-21%	-11%	12%
F 1StDetached	-28%	-14%	15%
F 2StDetached	-29%	-15%	15%
F 2StSemiDet	-28%	-14%	15%
F 2StTerraced	-26%	-14%	14%
F 1StApartment	-31%	-16%	17%

Figure 3.8: Variation in Primary Energy Demand of PISW dwellings under different internal temperature scenarios, with respect to the standard DEAP assumptions.

	Energy Savings (kWh/m²/annum)			% Rebound	
	Standard to standard	Mid temp to standard	Low temp to standard	Mid temp to standard	Low temp to standard
C 1StDetached	32.7	-0.2	-31.0	101%	195%
C 2StDetached	47.0	11.9	-20.7	75%	144%
C 2StSemiDet	45.3	11.4	-19.9	75%	144%
C 2StTerraced	40.0	8.8	-19.8	78%	150%
C 1StApartment	33.7	10.5	-10.1	69%	130%
F 1StDetached	107.5	50.2	-4.3	53%	104%
F 2StDetached	140.0	80.2	23.3	43%	83%
F 2StSemiDet	135.5	78.0	23.6	42%	83%
F 2StTerraced	128.3	75.0	24.9	42%	81%
F 1StApartment	102.3	38.6	-21.0	62%	121%

Figure 3.9: Energy savings and % rebound, post retrofit of roof and solid wall insulation in PISW dwellings, for different pre and post retrofit internal temperature assumptions.

	Energy Savings (kWh/m²/annum)			% Rebound	
	Standard to standard	Mid temp to standard	Low temp to standard	Mid temp to standard	Low temp to standard
C 1StDetached	53.1	20.2	-10.6	62%	120%
C 2StDetached	69.0	34.0	1.3	51%	98%
C 2StSemiDet	69.3	35.4	4.1	49%	94%
C 2StTerraced	67.9	36.7	8.1	46%	88%
C 1StApartment	65.3	42.1	21.5	36%	67%
F 1StDetached	201.4	144.0	89.5	28%	56%
F 2StDetached	227.8	168.0	111.1	26%	51%
F 2StSemiDet	234.5	176.9	122.6	25%	48%
F 2StTerraced	234.1	180.7	130.7	23%	44%
F 1StApartment	119.5	55.7	-3.9	53%	103%

Figure 3.10: Energy savings and % rebound, post retrofit of roof & solid wall insulation, boiler & heating controls upgrade, solar hot water & high efficiency windows in PISW dwellings, for different pre and post retrofit internal temperature assumptions.

	Existing	Obsolete	Retrofit
Un-Insulated Solid Wall	19%	60%	5%
Un-Insulated Cavity Wall	12%	20%	90%
Partially Insulated Solid Wall	18%	20%	5%
Insulated Wall	51%	0%	0%

Figure 4.1: Percentage of dwellings assumed obsolete and retrofitted in 2012, by wall type.

	Number available by wall type for retrofitting; 375k scenario									
	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Un-Insulated Solid Wall	166,988	159,763	151,191	141,245	124,714	94,620	64,432	34,150	3,777	0
Un-Insulated Cavity Wall	106,618	104,210	79,319	31,936	0	0	0	0	0	0
Partially Insulated Solid Wall	159,927	157,519	153,814	148,804	134,772	107,210	79,584	51,896	24,148	0
Insulated Wall	448,429	448,429	448,429	448,429	448,429	443,429	438,429	433,429	428,429	408,089
	Percent retrofitted by wall type; 375k scenario									
	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Un-Insulated Solid Wall		5%	5%	18%	45%	45%	45%	45%	11%	0%
Un-Insulated Cavity Wall		90%	90%	64%	0%	0%	0%	0%	0%	0%
Partially Insulated Solid Wall		5%	5%	18%	45%	45%	45%	45%	69%	0%
Insulated Wall		0%	0%	0%	10%	10%	10%	10%	20%	100%
	Number available by wall type for retrofitting; 750k scenario									
	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Un-Insulated Solid Wall	166,988	159,763	149,920	120,947	88,448	55,854	23,166	0	0	0
Un-Insulated Cavity Wall	106,618	104,210	56,861	0	0	0	0	0	0	0
Partially Insulated Solid Wall	159,927	157,519	152,543	126,038	96,039	65,976	35,850	3,068	0	0
Insulated Wall	448,429	448,429	448,429	448,429	398,429	348,429	298,429	241,406	131,354	48,089
	Percent retrofitted by wall type; 750k scenario									
	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Un-Insulated Solid Wall		5%	22%	25%	25%	25%	23%	0%	0%	0%
Un-Insulated Cavity Wall		90%	57%	0%	0%	0%	0%	0%	0%	0%
Partially Insulated Solid Wall		5%	22%	25%	25%	25%	25%	3%	0%	0%
Insulated Wall		0%	0%	50%	50%	50%	52%	97%	100%	100%

Figure 4.2: Percentage of dwellings retrofitted and number of dwellings available for retrofit by wall type.

Primary energy savings (GWh); 750k scenario									
Scenarios:	2012	2013	2014	2015	2016	2017	2018	2019	2020
Shallow	328	827	974	1,120	1,267	1,409	1,478	1,523	1,543
Deeper	587	1,656	2,396	3,137	3,877	4,610	5,211	5,628	5,807
BEH Max	620	1,965	3,026	4,088	5,149	6,188	6,804	7,221	7,400
Further	664	2,100	3,306	4,511	5,717	6,901	7,706	8,258	8,494
Primary energy savings (GWh); 375k scenario									
Scenarios:	2012	2013	2014	2015	2016	2017	2018	2019	2020
Shallow	164	492	759	864	970	1,076	1,182	1,239	1,249
Deeper	294	881	1,426	1,854	2,282	2,710	3,138	3,400	3,489
BEH Max	310	930	1,591	2,308	3,025	3,741	4,458	4,867	4,957
Further	332	996	1,703	2,472	3,242	4,012	4,781	5,230	5,348

Figure 4.3: Primary energy savings (GWh) from BEH, for all scenarios

Year		Number of appliances as % of number of dwellings				
		Clothes Dryer	Washing Machine	Dish washer	Refrigerator	Separate Freezer
1987	Historical records	22%	77%	8%	89%	16%
1988		22%	78%	9%	90%	17%
1989		23%	80%	10%	92%	17%
1990		24%	81%	12%	93%	18%
1991		24%	82%	13%	95%	19%
1992		25%	83%	14%	96%	20%
1993		25%	84%	16%	98%	21%
1994		26%	86%	17%	99%	22%
1995		27%	87%	19%	101%	23%
1996		30%	88%	21%	101%	24%
1997		33%	89%	24%	102%	25%
1998		36%	91%	27%	102%	27%
1999		39%	92%	29%	103%	28%
2000		42%	93%	32%	104%	29%
2001		46%	94%	36%	104%	30%
2002		50%	94%	39%	105%	32%
2003		54%	95%	43%	106%	33%
2004		58%	95%	46%	106%	34%
2005		62%	95%	50%	107%	35%
2006	Future projection	66%	96%	54%	107%	37%
2007		70%	96%	57%	108%	38%
2008		73%	96%	61%	108%	39%
2009		76%	97%	65%	109%	40%
2010		78%	97%	68%	109%	42%
2011		80%	97%	72%	109%	43%
2012		82%	97%	75%	109%	44%
2013		83%	97%	77%	109%	45%
2014		84%	97%	79%	109%	47%
2015		85%	98%	81%	109%	48%
2016		86%	98%	83%	110%	49%
2017		87%	98%	84%	110%	50%
2018		87%	98%	85%	110%	52%
2019		88%	98%	86%	110%	53%
2020		88%	98%	86%	110%	54%

Figure 5.4: Historical and projected penetration levels of domestic white appliances

Appendix B: Description of DEAP

Purpose of the Dwelling Energy Assessment Procedure

DEAP was developed by the Sustainable Energy Authority Ireland (SEAI) as a tool to demonstrate the compliance of new dwellings to part L of the building regulations, governing the conservation of fuel and energy, and to produce Building Energy Rating (BER) labels and reports, as required by the Energy Performance of Buildings Directive (EPBD)(EU 2002) A detailed description of the inputs and outputs for the DEAP calculation procedure can be found on the SEAI website (EU 2002; SEAI 2012a; SEAI 2012c; SEAI 2012d). The BER is an asset rating used to compare the energy efficiency of different dwellings. In order to compare like with like, for the DEAP calculation all dwellings are assumed to be heated to a standard internal temperature, for a standard number of heating periods each week. It requires as inputs a detailed description of the building envelope and heating system. The procedure takes account for space heating, water heating and lighting, as well as reduction in imported energy due to sustainable energy generation technologies. The DEAP calculation framework is based on IS EN 13790(ISO 2008), and draws heavily on the calculation procedures and tabulated data of the UK Standard Assessment Procedure(DECC 2005).

Overview of modules used in calculation

A brief description of some of the inputs under the different calculation modules within DEAP is given below:

- Dimensions: Takes as inputs the floor area, room height and living area fraction. Calculates the dwelling volume.
- Ventilation: Takes as inputs the numbers of various openings (chimneys, flues etc), structural air tightness, ventilation method. Calculates the air changes per hour.
- Building Elements: Takes as inputs the construction type, area and U-value of floors, roofs, walls, doors and windows. Calculates the total heat loss from glazing and opaque elements. Tests for conformity with maximum average and elemental U-value requirements.
- Water Heating: Takes as inputs whether or not there are distribution or storage losses, the volume of hot water tank, the level of insulation on tank and pipes. Calculates storage losses and energy

outputs based on an estimation of the daily hot water demand. This is automatically calculated based on a standard consumption per occupant, the number of occupants being itself automatically calculated as a function of the floor area.

- Lighting and Internal Gains: Takes as inputs the percentage of lighting that is low energy, e.g. CFL. Calculates the annual lighting energy demand. The internal gains section calculates the net internal heat gains due to lighting, the water heating system, metabolic gains, appliances & cooking and the heat loss to the cold water network. The figures for metabolic gains, appliances & cooking and losses to the cold water network are calculated automatically based on floor area and number of occupants, as per the water demand calculations.
- Net Space Heat Demand: Takes as inputs the thermal mass category of the building. Set values are used for the required temperature of living and non living areas and the length of unheated periods in a week. Calculates the annual space heating use.
- Distribution System Losses and Gains: Takes as inputs data on the heating system controls and responsiveness.
- Energy Requirements: Takes as inputs the efficiency of space and water heating systems, fuel type and presence of renewable energy technologies. Calculates the energy required by space and water heating systems, as well as the energy required by pumps and fans.
- Results: Displays the results of the energy demand calculation in terms of delivered energy, primary energy and CO_2 emissions for main and secondary space and water heating, pumps & fans and energy for lighting.

Summary of assumptions regarding internal temperatures, degree days and heating periods.

For the purpose of producing BER certificates, DEAP assumes all dwellings are heated to a standard internal temperature, for a standard number of heating periods each week. DEAP assumes two temperature zones in each dwelling, the living area and non-living area. The fraction of floor area that is living area is a dwelling specific variable. Standard assumptions are for a living area temperature of 21degC and a non living area temperature of 18degC during heating periods. The living area fraction is used to calculate the average internal temperature across the whole dwelling and this is used for heat loss calculations. The standard heating profile used is of 2 unheated periods of 8 hours duration each day. No differentiation is used between weekdays and weekends. It is assumed that during heating periods the standard internal temperatures are constantly achieved. The final heat loss calculation is based on a monthly adjusted internal temperature, calculated based on the monthly mean external temperature, the mean internal temperature required during heating periods and an intermittency temperature factor which accounts for the rate of heat loss during unheated periods. The latter is calculated based on the internal heat capacity of the dwelling which is specified in one of 5 bands for each dwelling. Similarly the daily hot water service demand in litres is automatically calculated based on standard assumptions on litres per occupant, with the number of occupants being itself automatically calculated as a function of the floor area.

An internal gains section calculates the net internal heat gains due to lighting, the water heating system, metabolic gains, appliances & cooking and the heat loss to the cold water network. The figures for metabolic gains, appliances & cooking and losses to the cold water network are based on standard calculations taking into account floor area and number of occupants.

NAS database of BER Results

The results of every BER carried out as well as the large amount of data collected on the physical characteristics of each dwelling required for the associated DEAP calculation are stored by SEAI in what is known as the National Administration System (NAS) database. This NAS data has been made publicly available for research purposes through the National BER Research Tool, hosted on the SEAI website(SEAI 2012b). This is a live database and is updated regularly, As of mid 2012 this database contained details of approx 300,000 dwellings, out of a total dwelling stock of 1.6 million. The full list of data fields publicly available is given in Figure A.1 below.

All NAS Variables	Input to DEAP model?	All NAS Variables	Input to DEAP model?	All NAS Variables	Input to DEAP model?
CountyName		PercentageDraughtStripped	Yes	gsdHSSupplHeatFraction	
DwellingTypeDescr		NoOfSidesSheltered	Yes	gsdHSSupplSystemEff	
Year_of_Construction		PermeabilityTest	Yes	DistLossFactor	
TypeofRating		PermeabilityTestResult	Yes	CHPUnitHeatFraction	
EnergyRating		TempAdjustment	Yes	CHPSystemType	
BerRating		HeatSystemControlCat	Yes	CHPElecEff	
GroundFloorArea(sq m)		HeatSystemResponseCat	Yes	CHPHeatEff	
UValueWall		NoCentralHeatingPumps	Yes	CHPFuelType	
UValueRoof	Yes	CHBoilerThermostatControlled	Yes	SupplHSFuelTypeID	
UValueFloor	Yes	NoOilBoilerHeatingPumps	Yes	gsdSHRenewableResources	
UValueWindow	Yes	OBBoilerThermostatControlled		gsdWHRenewableResources	
UvalueDoor	Yes	OBPumpInsideDwelling		SolarHeatFraction	
WallArea	Yes	NoGasBoilerHeatingPumps	Yes	DeliveredLightingEnergy	
RoofArea	Yes	WarmAirHeatingSystem	Yes	DeliveredEnergyPumpsFans	
FloorArea	Yes	UndergroundHeating	Yes	DeliveredEnergyMainWater	
WindowArea	Yes	GroundFloorUValue	Yes	DeliveredEnergyMainSpace	
DoorArea	Yes	DistributionLosses	Yes	PrimaryEnergyLighting	
NoStoreys	Yes	StorageLosses	Yes	PrimaryEnergyPumpsFans	
CO2Rating		ManuLossFactorAvail	Yes	PrimaryEnergyMainWater	
MainSpaceHeatingFuel	Yes	SolarHotWaterHeating	Yes	PrimaryEnergyMainSpace	
MainWaterHeatingFuel	Yes	ElecImmersionInSummer	Yes	CO2Lighting	
HSMainSystemEfficiency	Yes	CombiBoiler		CO2PumpsFans	
MultiDwellingMPRN		KeepHotFacility		CO2MainWater	
TGDLEdition		WaterStorageVolume	Yes	CO2MainSpace	
MPCDERValue		DeclaredLossFactor	Yes	GroundFloorArea	Yes
HSEffAdjFactor	Yes	TempFactorUnadj	Yes	GroundFloorHeight	Yes
HSSupplHeatFraction	Yes	TempFactorMultiplier	Yes	FirstFloorArea	Yes
HSSupplSystemEff	Yes	InsulationType	Yes	FirstFloorHeight	Yes
WHMainSystemEff	Yes	InsulationThickness	Yes	SecondFloorArea	Yes
WHEffAdjFactor	Yes	PrimaryCircuitLoss	Yes	SecondFloorHeight	Yes
SupplSHFuel	Yes	CombiBoilerAddLoss		ThirdFloorArea	Yes
SupplWHFuel	Yes	ElecConsumpKeepHot		ThirdFloorHeight	Yes
SHRenewableResources		ApertureArea	Yes	ThermalBridgingFactor	Yes
WHRenewableResources		ZeroLossCollectorEff	Yes	ThermalMassCategory	Yes
NoOfChimneys	Yes	CollectorHeatLossCoEff	Yes	PredominantRoofTypeArea	
NoOfOpenFlues	Yes	AnnualSolarRadiation	Yes	PredominantRoofType	
NoOfFansAndVents	Yes	OvershadingFactor	Yes	LowEnergyLightingPercent	Yes
NoOfFluelessGasFires	Yes	CylinderStat	Yes	TotalDeliveredEnergy	
DraftLobby	Yes	SolarStorageVolume	Yes	DeliveredEnergySecondarySpace	
VentilationMethod	Yes	VolumeOfPreHeatStore	Yes	DeliveredEnergySupplementaryWater	
FanPowerManuDeclaredValue	Yes	CombinedCylinder	Yes	LivingAreaPercent	Yes
HeatExchangerEff	Yes	ElectricityConsumption		CO2SecondarySpace	
StructureType	Yes	SWHPumpSolarPowered	Yes	CO2SupplementaryWater	
SuspendedWoodenFloor	Yes	ChargingBasisHeatConsumed	Yes	PrimaryEnergySecondarySpace	
				PrimaryEnergySupplementaryWater	

Figure B.1

Appendix B References

DECC (2005). The Standard Assessment Procedure for Energy Rating of Dwellings, UK Department of Energy and Climate Change.

EU (2002). Directive 2002/91/EC of the European Parliament and of the Council of 16 Dec 2002 on the energy performance of buildings. EU.

ISO (2008). ISO 13790:2008 Energy performance of buildings -- Calculation of energy use for space heating and cooling. ISO.

SEAI. (2008). "Dwelling Energy Assessment Procedure (DEAP) 2006 EDITION, VERSION 2.2: Irish official method for calculating and rating the energy performance of dwellings
", from http://www.sei.ie/uploadedfiles/InfoCentre/BER/DEAP__Version_2.2_Manual_February_2008.pdf.

SEAI. (2012a). "Dwelling Energy Assessment Procedure." from http://www.sei.ie/Your_Building/BER/BER_Assessors/Technical/DEAP/.

SEAI. (2012b). "National BER Research Tool." from http://www.seai.ie/Your_Building/BER/National_BER_Research_Tool/.

SEAI. (2012c). "BER What is it?", from http://www.seai.ie/Your_Building/BER/BER_FAQ/FAQ_BER/General/BER_what_is_it_.html.

SEAI. (2012d). "DEAP Manual Version 3.2.1." from http://www.seai.ie/Your_Building/EPBD/DEAP/.

Appendix C: Input data for DEAP modelling

Table C.1 below shows the input data for the DEAP model of new dwellings constructed to the 2005 building regulations.

Input Variable	Dwelling Type	
	All except Apartment	Apartment
GroundFloorArea(sq m)	Variable	
Wall Area	Calculated based on floor area	
RoofArea	Calculated based on floor area	
Floor Area	Calculated based on floor area	
Window Area	Calculated based on floor area	
Door Area	Calculated based on floor area	
U-Value Wall	0.27	
U-Value Roof	0.16	
U-Value Floor	0.25	
U-Value Window	2	
U-Value Door	2	
Main Space Heating Fuel	Gas	
Main Water Heating Fuel	Gas	
Main Space Heating Efficiency (%)	92	
Main Space Heating Efficiency Adjustment Factor	1	
Secondary Space Heating Fraction (%)	10	
Secondary Space Heating Efficiency (%)	28	N/A
Main Water Heating Efficiency (%)	92	
Main Water Heating Efficiency Adjustment Factor	1	
Secondary Space Heating Fuel	Solid Multi Fuel	None
Secondary Water Heating Fuel	Electricity	
Number of Chimneys	2	0
Number of Open Flues	0	0
Number of Fans and Vents	10	5
Number of Flueless Gas Fires	0	0
Draft Lobby	No	
Ventilation Method	Natural	
Structure Type	Masonry	
Suspended Wooden Floor	No	
Percentage Draught Stripped	100%	
Number of Sides Sheltered	2	3
Permeability Test	No	
Temperature Adjustment Factor	2	
Heat System Control Category	2	
Heat System Response Category	1	
Number of Central Heating Pumps	1	
Central Heating Boiler Thermostat Controlled	Yes	
Number of Gas Boiler Heating Pumps	1	
Warm Air Heating System	No	
Underground Heating	No	
Distribution Losses	Yes	
Storage Losses	Yes	
ManufLossFactorAvail	No	
SolarHotWaterHeating	No	
ElecImmersionInSummer	Yes	
WaterStorageVolume (litres)	120	75
InsulationType	Factory insulated	
InsulationThickness (mm)	35	
PrimaryCircuitLoss (kWh/y)	360	
ThermalBridgingFactor (W/m^2/K)	0.11	
ThermalMassCategory	Medium-high	
LowEnergyLightingPercent	100	
LivingAreaPercent %	20	40

Table C.1: *Input data for DEAP model of new dwellings built to 2005 building regulations*

Appendix D: Data on dwelling types for Chapter 2

Shown in Table D.1 and Table D.2 below is the data used in Chapter 2 for the development of an archetype model of space and water heating of new dwellings. Based on this data the future stock of new dwellings was broken down into five dwelling types: bungalow/one storey detached house, detached house/ two storey detached house, semi-detached house. terraced house, apartment.

	2002	2006
Detached	562,818	625,988
Semi-detached	343,301	398,360
Terraced	236,422	257,522
Flat	110,458	139,872
Caravan, mobile or other t	8,341	7,225
Not stated	26,618	31,803

Table D.1: *CSO Data on dwelling type from 2008*

	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Bungalow	6,077	6,748	6,645	7,451	7,343	8,221	9,070	9,029	8,870	8,934	6,665			
Detached House	4,447	5,462	8,583	9,552	9,631	12,962	14,828	15,471	13,157	13,276	13,516			
Individual House												20,362	22,806	19,663
Semi-D House	9,362	10,395	10,023	12,511	14,368	14,036	14,470	14,006	18,633	23,522	37,736			
Terraced House	1,442	1,558	1,400	1,626	1,469	1,697	2,158	3,070	4,997	7,848	2,531			
Scheme House												42,160	50,267	39,273
Flat /Apartment	5,112	6,009	6,670	7,302	9,137	9,196	8,886	10,626	11,638	14,839	16,106	18,035	19,946	18,691
Total	26,440	30,172	33,321	38,442	41,948	46,112	49,412	52,202	57,295	68,419	76,554	80,557	93,019	77,627

Table D.2: *Department of the Environment data on dwelling type from 2008*

Appendix E: Long term demand for new dwellings

House building grew rapidly through the long years of the boom, rising from around 20,000 in 1992 to peak at around 90,000 in 2006. While the peak of 90,000 dwellings per annum was widely acknowledged as unsustainable, it was expected that the medium term demand up to 2020 would remain strong, with the 2009 NEEAP estimating that the housing market would recover from a contraction down to 20,000 completions in 2009 to a more sustainable rate of 45,000 completions per annum in the period 2015 to 2020. For analysis on underlying drivers of long term demand for new dwelling in Ireland it is worth quoting the 2009 European Housing Review. In its chapter dealing specifically with Ireland it states:

"*There is a long history of poor housing conditions. In 1980, the country had the lowest number of dwellings per thousand inhabitants in the old EU. It still has worse housing conditions than other countries with similar living standards, despite the recent building boom, with floor areas per person of around a fifth less than the western European average4. Household size is also relatively high at 2.94 persons in 2002, though it had improved from 3.34 in 19915. Undoubtedly, the historic lack of dwellings was a root cause of the recent long housing boom.*"

On the demographic influences driving demand for dwellings it states:

"*Demographic factors continue to stimulate underlying demand. The population reached a low point of 2.8 million in 1961 but since then has risen by 50% to 4.24 million. It rapidly grew by 2% annually from 2002 to 2006, both because of high natural increase and immigration. In addition, the age range from 20-44 has been increasing at more than twice the rate of the population as a whole. This age group comprises a key sector in the housing market, both as new entrants and as traders up when children come along. The fertility rate is now similar to that of many other European countries. The number of births grew by almost third between 1994 and 2006, because of a bulge increase in women aged between 20 and 39 years, who were born at an earlier time when fertility rates were much higher. This characteristic is currently increasing the demand for accommodation sufficiently large to bring up children in relatively affluent families. The population is forecast to increase quite rapidly over the next 35 years, according to recent CSO estimates. Moreover, household numbers are* *growing much faster than the population as a whole. Over 450,000 households were added between 1990 and 2003, a 36% increase. Relative household size is still towards the higher end of the EU range, so there is further scope for above average increases in household numbers.*"

In conclusion it cautions:

"*The demographic factors discussed above suggest some ways in which the housing market might change in the future. However, it is important to remember two factors. First, demographic forecasting is fraught with difficulties and forecasts are subject to error. The mid-1990s projections, for example, substantially underestimated population growth in the 2000s. Second, demographic factors constitute only one element in determining aggregate housing demand. Economic considerations are also important and influential in demographic outcomes.*"

A thorough analysis of the housing market in Ireland in the period to 2020 is outside the scope of this work. The author provides for comparison the model projections used in the original 2009 model with the latest data on housing completions from the Department of the Environment. It can be seen that as of 2012 the housing construction market had failed to recover and has bottomed out at approximately 10,000 completions per annum. preliminary data from 2013 suggests that completion have remained constant at this level. However little can be inferred as to what the long term stable rate may be from these figures.

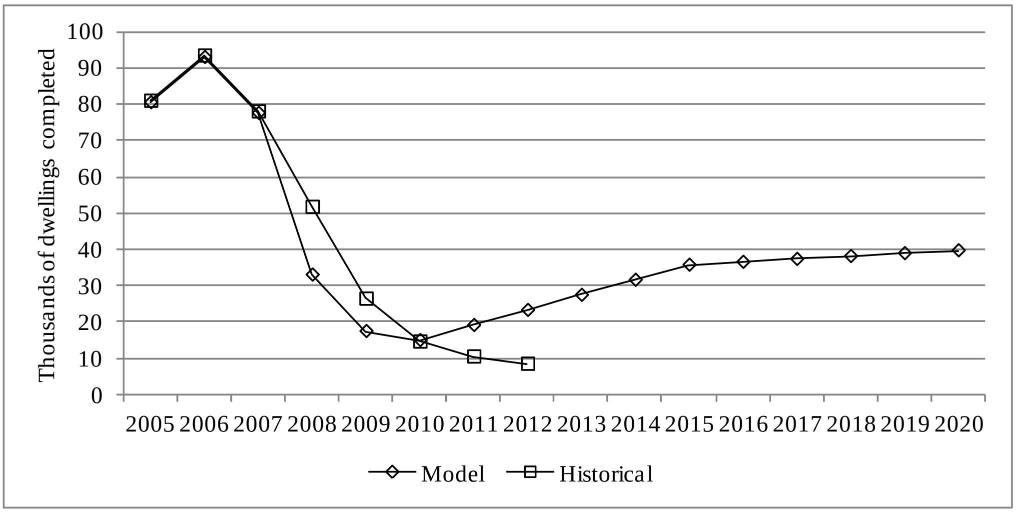

Figure E.1: *Numbers of dwellings completed in model and up to date historical*

Yeal	Dwellings Completed Model	 Historical
2005	80,557	80,957
2006	93,019	93,419
2007	77,627	78,027
2008	33,054	51,724
2009	17,500	26,420
2010	15,000	14,602
2011	19,156	10,480
2012	23,312	8,488
- 2015	35,779	
- 2020	39,755	

Table E.1 *Numbers of dwellings completed in model and up to date historical*

Appendix F: Floor Area Data

Up to date quarterly statistics on dwelling floor area from the CSO are provided in Table F.1. The projections made at the time of modelling for floor area of houses and apartments based on data up to 2006, along with up to date annual statistics up to 2012 are given in Table F.2. It can be seen that in the fourth quarter of 2006, the last year for which historical data was available at the time of modelling the average new house for which planning permission was sought had a floor area of 161m^2, the average apartment was 82m^2, while the average detached house was 227m^2. The latest data from 2013 shows that this has increased to 187m2, 117m^2 and 250m^2 for all houses, apartments and detached houses respectively. For comparison Table F.3 also provides data from the 2010 Housing Statistics in the European Union report which gives what data is available on floor areas across EU member states. here it can be seen that while Ireland is at the upper end of the spectrum it is not an outlier, with Luxembourg and Cyprus and Luxemburg having average floor areas for all dwellings of 180m^2 and 198m^2 respectively.

Quarter	Average Floor area of dwellings seeking planning permission, m^2			
	Houses	Multi development houses	One off houses	Private flats / apartments
2001Q1	147	131	182	78
2001Q2	149	134	188	77
2001Q3	153	134	188	79
2001Q4	147	126	186	78
2002Q1	145	122	188	80
2002Q2	138	121	191	76
2002Q3	145	118	196	77
2002Q4	149	120	195	79
2003Q1	154	122	196	81
2003Q2	144	118	198	81
2003Q3	141	114	199	78
2003Q4	151	123	203	78
2004Q1	147	119	202	77
2004Q2	149	119	205	74
2004Q3	151	121	206	78
2004Q4	145	118	207	77
2005Q1	149	125	211	76
2005Q2	145	123	211	80
2005Q3	152	125	215	80
2005Q4	152	124	218	77
2006Q1	152	124	219	80
2006Q2	161	132	225	78
2006Q3	162	130	227	85
2006Q4	161	127	227	82
2007Q1	162	130	235	82
2007Q2	160	134	237	83
2007Q3	165	132	238	85
2007Q4	170	136	242	91
2008Q1	165	131	242	84
2008Q2	178	146	247	86
2008Q3	166	128	249	88
2008Q4	166	127	253	84
2009Q1	165	132	252	97
2009Q2	165	129	253	92
2009Q3	180	133	251	95
2009Q4	193	138	256	87
2010Q1	186	138	250	85
2010Q2	180	125	253	98
2010Q3	196	139	250	92
2010Q4	204	140	248	90
2011Q1	172	126	250	109
2011Q2	187	139	251	99
2011Q3	206	146	248	118
2011Q4	196	129	249	88
2012Q1	212	135	248	81
2012Q2	220	143	251	102
2012Q3	196	145	243	85
2012Q4	199	143	250	93
2013Q1	186	143	246	102
2013Q2	187	135	250	117

Table F.1: *CSO data on average floor area of dwellings seeking planning permission by quarter*

Year	Average floor area, m^2			
	Model Floor Area Houses*	Historical Floor Area Houses	Model Floor Area Apartments*	Historical Floor Area Apartments
2001	149	149	78	78
2002	144	144	78	78
2003	147	148	79	80
2004	148	148	77	77
2005	149	149	78	78
2006	159	159	81	81
2007	156	164	83	85
2008	159	168	84	85
2009	161	176	87	93
2010	163	192	88	91
2011	165	190	89	103
2012	167	207	90	90
2013	169		91	
2014	170		92	
2015	172		94	
2016	174		95	
2017	177		96	
2018	179		97	
2019	182		99	
2020	184		101	

*At time of modelling historical data up to 2006 was available and this was projected forward to 2020.

Table F.2: *Average floor area of dwellings used in model and more recent historical CSO data*

	Year	Total dwelling stock (m^2/dwelling)	Year	Dwellings completed (m^2/dwelling)
Austria	2009	98.5	2002	101
Belgium	2001	81.3	2005	105
Bulgaria	2008	63.9	2008	88.2
Cyprus	-	na	2002	197.6
Czech Republic	2001	76.3	2008	107
Denmark	2009	114.4	2008	131.5
Estonia	2009	61.2	2009	100.8
Finland	2009	79.4	2008	101.7
France	2006	91	2006	99
Germany	2006	89.9	2008	113.6
Greece	2001	81.3	2001	124.6
Hungary	2005	77.7	2009	88.8
Ireland	2003	104	2003	105
Italy	2001	96	2007	73.5
Latvia	2008	58.5	2008	142.7
Lithuania	2008	62.9	2003	106.2
Luxembourg	2008	133.5	2007	180.4
Malta	2002	106.4	-	na
Netherlands	2000	98	2000	115.5
Poland	2008	70.2	2008	104
Portugal	2001	83	2008	96.2
Romania	2008	38.7	2008	70
Slovak Republic	2001	56.1	2009	116.2
Slovenia	2004	75.6	2004	108.7
Spain	2008	99.1	2008	116
Sweden	2008	92.8	2009	99.1
United Kingdom	2001	86.9	1981-2001	82.7

Table F.2: Data on typical floor areas for EU member states from: Dol, K. and M. Haffner (2010); Housing Statistics in the European Union 2010.

Appendix G: Data on cavity wall insulation from the NSHQ 2001/02

The National Survey of Housing Quality (NSHQ) contained two questions each with three possible responses relating to the presence of cavity walls and whether or not these were insulated. The questions and responses are given below

NSHQ Q62 Cavity Walls

- No
- Some
- All

NSHQ Q63 Cavity wall Insulation

- No
- Some
- All

The breakdown of the results is given in table C1

Responce to NSHQ	Detached house	Semi-detached house	Terraced house	Apartment	Total
don't know if cavity wall	1,350	500	382	34	2,266
no cavity wall	1,549	1,951	1,879	307	5,686
cavity wall; don't know if insulated	5,870	1,802	2,539	230	10,441
cavity wall; some insulated	10,146	3,155	1,427	160	14,888
some cavity wall; insulated	2,163	1,214	778	15	4,170
cavity wall; not insulated	530	622	457	29	1,638

Table G.1: *NSHQ data on the nature of wall insulation present in homes.*