

2019-10

Thermal Refurbishment Status of the Irish Housing Stock

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Recommended Citation

Ahern, C., Norton, B., (2019). Thermal energy refurbishment status of the Irish housing stock. *Energy and Buildings* 202, 109348. doi:10.1016/j.enbuild.2019.109348

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Revision ENB_2019_1842_Thermal energy refurbishment status of the Irish housing stock

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Highlights

1. Establishes the thermal refurbishment status of the Irish Housing stock as of 2014.
2. Methodology is generalizable to energy performance certification datasets across Europe.
3. Significant levels of thermal refurbishments were found.
4. Average energy efficiency of Irish housing has improved by 34 % between 1995 and 2001.
5. Finds the assumption of Irish housing being energy sub-standard is no longer valid.

Abstract

Energy Performance Certificates (EPCs) are issued for buildings constructed, sold or leased across the EU. Using a generalizable methodology this work exploits Ireland's EPC national dwelling stock database to determine the thermal refurbishment status of Ireland's housing stock. It is estimated in 2014 that; i) 58 % of walls were insulated at a mean overall heat loss coefficient or U-value of 0.66 W/m²K, ii) 67 % of roofs were insulated at a mean U-value 0.37 W/m²K, iii) 97 % of windows were double-glazed, and iv) 53 % of floors were insulated to a mean U-value of 0.59 W/m²K. The (i) extent of thermal refurbishments and (ii) high degree of energy-efficiency improvements in Ireland contribute significantly to household energy usage per square metre being 9 % below the EU 27 average in 2010, and the average energy efficiency of Irish housing having improved by over 34 % between 1995 and 2011 (2.5 % per annum). The distinction between the thermal efficiency of pre-thermal building regulation and post-thermal building regulation dwellings, whilst still valid, is lessening. A strong association between dwelling age and energy efficiency often-made is diminishing as retrofits continue to be carried out. The long-held view that the majority of Irish dwellings are thermally sub-standard is no longer valid.

Key Words

Irish housing stock, Refurbishment Status, Renovation Status, Retrofit Status, Detached Housing, Residential Sector, Energy Efficiency, Thermal Retrofit, Thermal Efficiency, Retrofitting, Refurbishment, Existing Buildings, Existing Housing, Domestic Energy Use

Abbreviations

1S	Single Storey
2S	Two Storey
CIBSE	Chartered Institute of Building Services Engineers
DEAP	Dwelling Energy Assessment Procedure
EPBD	European Performance of Buildings Directive
EPC	Energy Performance Certificate
EU-27/28	Total EU member countries as of time of publication
INSHQ	Irish National Survey of Housing Quality
NEEAP	National Energy Efficiency Action Plan
SEAI	Sustainable Energy Authority of Ireland (formerly Sustainable Energy Ireland - SEI)
TABULA	Typology Approach for Building Stock Energy Assessment

1.0 Introduction

1.1 Policy Contexts

Households consume 27 % of end-use energy in the European Union (EU) [1]. It is such a large proportion because 67 % of European housing was built prior to 1980 [2], before the pervasive introduction of thermal building regulations for housing. The extent and duration of the dominance of the characteristics of pre-existing houses on housing energy use depends on the construction rate, floor areas and specifications of new dwellings [3]. As average replacement rates for existing housing stocks in the EU are less than 0.1 % [4], the majority of Europe's existing dwellings will still be in place in 2050 [5]. In the United Kingdom for example around 75 % of dwellings that will exist in 2050 have already been constructed [6]. Accordingly, to achieve less overall residential energy use requires (i) energy refurbishment of existing dwellings [3, 7-10], and (ii) greater efficiency in the production and distribution systems that provide energy to dwellings. This

paper provides an understanding of the extent that refurbishments have already improved the thermal energy performance of existing dwellings.

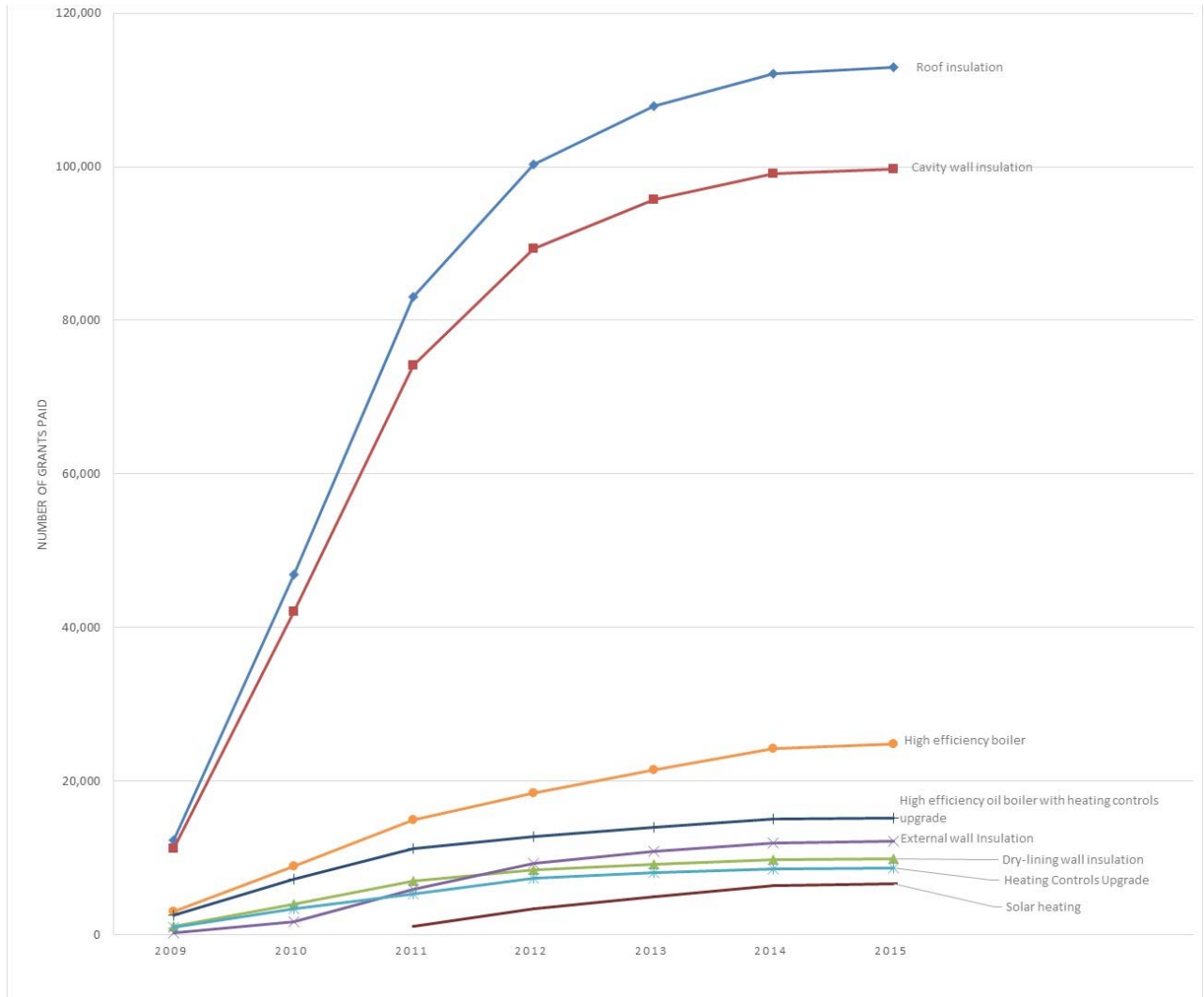
The 2010 EU Energy Performance of Buildings Directive (EPBD recast, 2010/31/EU) [11] requires EU Members States (MSs) to set minimum energy performance requirements [12] for; (a) new buildings, (b) major renovation of buildings and, (c) replacement or retrofit of windows, roof, walls and/or heating and cooling systems. The 2012 EU Energy Efficiency Directive (2012/27/EU) [13] requires inclusion of long-term national building renovation strategies in each National Energy Efficiency Action Plan (NEAPP). In Ireland, the NEEAP seeks to [14]:

1. Create houses that meet expectations of comfort and functionality while significantly reducing energy use and CO₂ emissions; and
2. Improve older housing with poor energy and CO₂ performance.

Irish Government policy seeks to reduce built environment greenhouse gas emissions as close to zero as is technically and economically feasible by 2050 [15]. In Ireland, incentive schemes support energy efficiency upgrades to houses built before 2006. Building regulations for new construction ensure energy efficiency in new dwellings [16].

State-funded energy refurbishment grants partially pay for roof insulation, wall insulation (i.e cavity, external and dry-lining), heating systems upgrades and solar thermal collectors retrofitted to houses built before 2006. Over €202.4 million worth of grants has been paid to homeowners since the start of the scheme in 2009 until 2017, with a total 475,190 individual energy efficiency measures undertaken [17]. As shown in Figure 1, while state grant schemes have been successful in encouraging homeowners to carry out energy efficiency works, the majority of savings have come from lower cost, more accessible measures such as roof and cavity wall insulation [17].

Figure 1 – Number of state grants awarded by energy refurbishment measure (2009 to 2015)
[18]



The annual energy consumption of residential buildings in European Union (EU) is approximately 200 kWh/m² [1], of this, space heating consumed 68 % of energy used, accounting for 210 million tonnes of oil equivalent (Mtoe) or 244.23 TWh in 2009 [2]. 80 % to 90 % of the overall heat loss from dwellings is by heat transfer through the building fabric; 8 % to 16% is heat loss through air infiltration and 4 % to 16 % is heat loss through thermal conduction through linear thermal bridges [19]. To reduce heat loss through dwelling envelopes, Irish state agencies offer thermal refurbishment grants for dwelling fabric elements retrofitted to achieve U-Values shown in Table 1 [20].

Table 1 U-values to be achieved to receive state-funded thermal refurbishment grants in Ireland

		U-value (W/m ² K)	
Insulated Fabric Element	Wall	0.27	
	Roof	Ceiling	0.16
		Rafter	0.2

Energy Performance Certificates (EPCs) are issued for buildings constructed, sold or leased in the EU [21, 22]. In addition, Irish homeowners must also submit an EPC after refurbishment works to qualify for an energy refurbishment grant [17]. Cumulatively, EPC's thus provide empirical information that can determine the renovation status of the Irish dwelling stock.

A transparent generalisable methodology to create a stock model from a large empirical Energy Performance Certification (EPC) database using a 'bottom-up' approach was defined in other work [23]. Using Ireland's predominant housing typology as a representative case study dwelling, the objective of this work is to use Ireland's national EPC database to establish the thermal refurbishment status of the Irish housing stock in accordance with the generalizable methodology derived in [23].

1.2 Case Study – Ireland's Housing Stock

The residential sector in Ireland accounts for 27 % of all energy use emitting 10.5 million tonnes of CO₂ in 2017 [15]. 50 % of the current housing stock was constructed before thermal building regulations were introduced in 1979 [23]. It was not until 2006 that thermal retrofits became significant [23-28]. With higher than the EU average greenhouse gas emissions, Ireland's housing stock has been identified as being amongst the least energy efficient in Northern Europe [29, 30]. For example it has been stated that the average Irish Dwelling in 2005 emitted 47 % more CO₂ emissions than the average dwelling in the UK with emissions 92 % higher than the average for the EU-15 and 104 % more than the EU-27 [31].

At 149m², the mean-weighted-average heated floor area¹ of an Irish detached dwelling is approximately twice the average European floor area [2]. At 5.6 rooms per person Irish dwellings also have the greatest average number of rooms per dwelling in Europe in 2002 [32]. As shown in Figure 2, Ireland's predominant house typology, comprising 31 % of the pre-2006 stock, are detached, single-family dwellings [23]. As shown in Figure 3, at 90 % Ireland has the highest proportion, of single-family dwellings in Europe, the UK, Greece, Norway and The Netherlands have similar profiles [28].

Single-family dwellings constitute 49.4 % of the total building floor area in the EU [33]. 34 % of the EU 28 population lived in detached single-family houses in 2013 [28]. Detached dwellings, with relatively high surface area to volume ratios, exhibit larger heat losses than other dwelling types of the same construction period [34], tend to be heated for longer than other types [35], with higher cost of heating to a given comfort level [36]. Detached dwellings are therefore targeted in energy-efficiency retrofit programmes [35, 37, 38].

More generally, energy efficiency retrofits remain important as 67 % of European housing was built prior to 1980 [2], before the introduction of thermal building regulations for the housing sector. 70 % of Irish detached dwellings were constructed before thermal building regulations required higher levels of thermal insulation [24-28]. Detached dwellings in Ireland have a stronger association with fuel poverty than other dwelling types due to [23]; a) a higher cost of heating to a given comfort level [36], b) being 88 % occupied by those over 50 years old and c) being classified as 'hard to treat²' [39]. Older adults [38];

- spend more time at home than younger adults,
- are more likely to live in homes built before 1970 with lower thermal insulation standards than younger groups³,
- have a higher likelihood of living alone, whilst
- sedentary older adults prefer a minimum of a 2-3 °C higher internal temperature over the 18 °C minimum temperature recommended by the World Health Organisation [40].

¹ Mean (μ) of the sum of the floor areas by period of construction (m²) weighted by dwelling quantity per period of construction (N) given by the following equation; Mean weighted floor area = $\mu \times \sum$ [Floor area (m²) x dwelling quantity by period of construction (N)]

² Dwellings with solid walls, off the gas network or with no loft

³ 69 % of those aged 75 and over, versus 53 % of 65-74 year olds and 36 % of 50-64 year olds

Figure 2 Number of Irish dwellings by type [25]

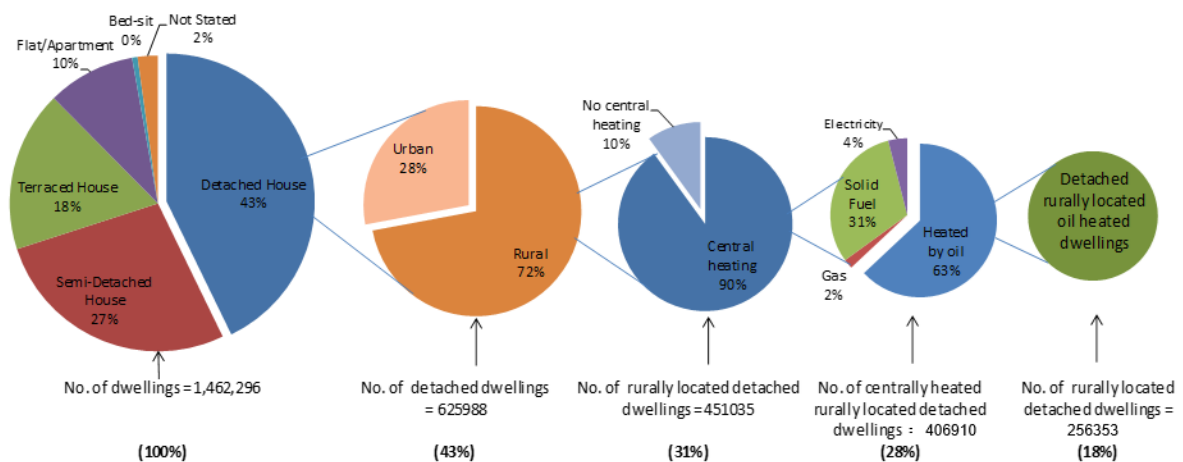
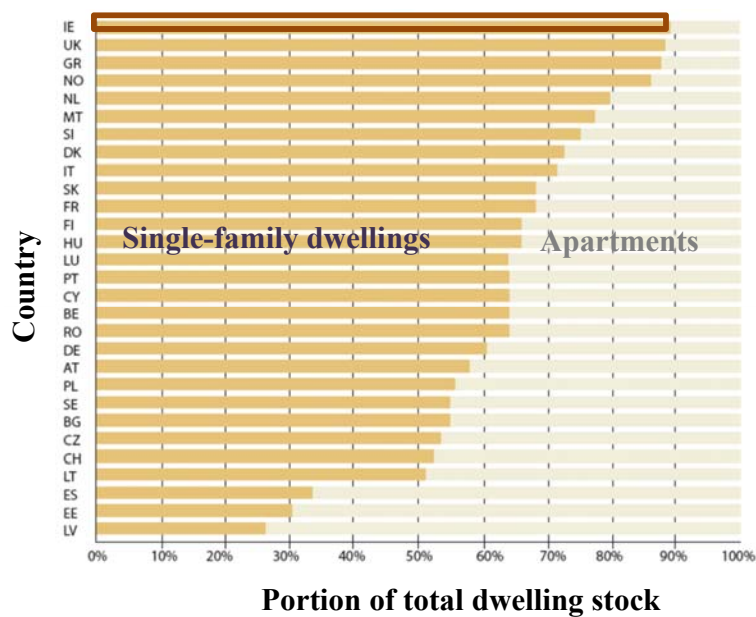


Figure 3 Distribution of single-family and apartment buildings in Europe [41]



2.0 Methodology

EPCs in Ireland are generated through a methodology embodied in the national Dwelling Energy Assessment Procedure (DEAP) software administered by the Sustainable Energy Authority of Ireland (SEAI). SEAI made this detailed national empirical EPC dataset publicly available in 2014 [42]. 463,582 dwellings representing 31.7 % of the total dwelling stock constructed up to 2006 that had received an EPC by August 2014 were examined in this case study [43]. Using Ireland’s

predominant single-family housing typology as a case study dwelling, this work establishes the thermal refurbishment status of the pre-2006 housing stock in 2014 using the national EPC database.

2.1 Segmentation

25 % (N=116,354) of the dwellings within the EPC database are detached, this is similar to the 28% of detached dwellings in Ireland that were recorded as centrally heated in the national 2006 census – see Figure 2. 60 % of detached dwellings within the EPC database are rurally located while an average of 76 % of rural homes were oil-heated equating to 19 % nationally [43]. This is similar to the 18 % of detached homes that were recorded as oil heated in the 2006 national census [25]. The relative sample sizes in the EPC dataset used are thus consistent with the national distribution of detached dwellings by construction period published by Ireland’s national statistics office [25, 43]. 97 % of detached dwelling are either single or two-storey, 98 % are naturally ventilated [43].

As shown in Figure 1, rural, single and two-storey, oil centrally-heated and naturally-ventilated dwellings are the predominant dwelling type in Ireland accounting for 18 % of the national dwelling stock and 63 % of all detached dwellings. Dwellings with these characteristics were isolated from the EPC dataset. To avoid inconsistencies, dwellings carrying a ‘provisional’ certificate were removed from the dataset. As shown in Table 3, this gave a sample of 50,236 dwellings, representing 12.35 % of the detached dwelling typology nationally.

2.1.1 Statistical significance of segmented EPC dataset

As described by Equation (1), margin of error (e), z-score (z) and standard deviation (σ) measure how well a sample (N_s) represents a population (N_p) [44];

$$Sample\ size\ (N_s) = \frac{\frac{z^2 \times \sigma(1-\sigma)}{e^2}}{1 + \left(\frac{z^2 \times \sigma(1-\sigma)}{e^2 N_p}\right)} \quad (1)$$

Where ‘z’ or ‘z-score’ is a standardised dimensionless quantity indicating how many standard deviations (σ) a random variable (X) is away from the mean (μ) and margin of error ‘e’ expresses the maximum expected difference between the true population parameter and a sample estimate of that parameter. The margin of error of a sample dataset (N_s) of a given population (N_p) is given by Equation (2)⁴ [45];

$$e = \sqrt{\frac{z^2 \times \sigma(1-\sigma) - \frac{N_s[z^2 \times \sigma(1-\sigma)]}{N_p}}{N_s}} \quad (2)$$

To be meaningful, the margin of error is qualified by a probability statement expressed as a confidence level (α) [45]. Confidence level indicates the percentage level of uncertainty with a statistic [45]. Generally, the larger the sample size, the more statistically significant it is, meaning there is less of a chance results of a survey happened by coincidence. A 100 % confidence level means there is no doubt that if the survey was repeated the same results would be returned. A 100 % confidence level doesn’t exist in statistics, unless the entire population was surveyed — and even then it is unlikely that the survey was not open to errors or biases [46].

A confidence level for a given mean value (μ) of a population (N_p) can be calculated using Equation (3) [45];

$$\bar{X} \pm z \frac{\alpha}{2} \times \frac{\sigma}{\sqrt{N_p}} \quad (3)$$

where \bar{X} is the mean of the sample (N_s) and α is the desired percentage confidence level.

Based on Equation (3), a standard normal table or Z-table is a mathematical table that returns z-scores for desired confidence levels, an extract of which is shown in Table 2.

⁴ Equation (1) rearranged in terms of ‘e’

Table 2 Z-scores and desired confidence levels [44]

Desired Confidence Level (α)	z-score
80 %	1.28
85 %	1.44
90 %	1.65
95 %	1.96
99 %	2.58

“Acceptable” margins of error fall between 4 % and 8 % at a 95 % confidence interval meaning that there is a 95 % confidence level that the sample is representative of the true population [47]. To ascertain whether the segmented sample population (N_s) of 50,236 detached is representative of the entire population (N_p) of 406,910, the margin of error at a 99 % confidence level (z-score 2.58) for each period of construction was calculated using Equation (1) with results shown in Table 3 for standard deviation (σ) of 0.5 (50 %). A value of 0.5 (50 %) for standard deviation (σ) was chosen for input to Equation (2) as this is the worst-case scenario percentage so guaranteeing that the margin of error calculated is worst-case.

Table 3 Frequency of detached dwellings in representative empirical dataset compared with actual dwelling frequency by period of construction [25, 43]

			Actual number and percentage of detached dwellings nationally (CSO dataset)		Sample number and percentage of detached dwellings (empirical EPC dataset)		Margin of error at confidence level of 99 %
			N (Population)	%	N (Sample)	%	
Period of Construction	Post-thermal regulation	2005-2006	21910	5%	3693	7%	2%
		2000-2004	52764	13%	8867	18%	1%
		1994-1999	45694	11%	7080	14%	1%
		1983-1993	60233	15%	8375	17%	1%
		1978-1982	29817	7%	5695	11%	2%
	Pre-thermal regulation	1967-1977	52457	13%	6559	13%	1%
		1950-1966	32245	8%	3662	7%	2%
		1930-1949	32453	8%	2110	4%	3%
		1900-1929	34552	8%	2901	6%	2%
		< 1900	44784	11%	1294	3%	4%
		Total/%		406910	100%	50236	100%

Because older dwellings change ownership less often, as shown in Table 3, there are fewer EPCs for older dwellings than for newer dwellings. Older dwellings are thus somewhat less represented in the sample than newer dwellings. Notwithstanding this, Table 3 shows acceptable margins of error in all cases, indicating a statistically representative sample while the sample number and proportion of detached dwellings in the empirical dataset is coherent with the actual number and proportion of detached dwellings nationally, so verifying intra-dataset consistency.

2.2 Analysis of microscopic data within EPC Dataset

A typical U-value frequency distribution for dwelling walls and roofs by construction period extracted from the Irish national EPC dataset [43] is bi-modally distributed. Referring to Figure 4:

- ‘Mode 2’ building elements are walls and roofs as constructed originally with U-values⁵ of 0.6 to 2.3 W/m²K.
- ‘Mode 1’ dwellings are thermally-upgraded building elements with lower U-values ranging between 0.1 to 0.59 W/m²K.

As more thermal retrofits are carried out more building elements U-values will fall within Mode 2 than Mode 1. The standard deviation⁵ for Mode 2 is greater than that of Mode 1 demonstrating that retrofits harmonise levels of thermal insulation. Floor U-values show a unimodal normal distribution as there are fewer retrofits due to the high replacement cost of floor coverings [48] together with the impracticality of retrofitting floor insulation.

Figure 4 highlights statistically anomalous spikes observed in the data split-across time-periods in both pre and post-regulation dwellings; in the tail of the Mode 2 empirical U-value distribution for exposed building elements such as walls and roofs. Analysis revealed these result from default U-value selection [19, 28]. Where acquiring data would be prohibitively costly, nationally-applicable default U-values are employed [26]. Use of such worst case default U-values ensure that a poor dwelling does not attain a better energy rating than is merited [28]. In the absence of empirical data in Ireland such default U-values, as in many other EU member states, are set by the type and date of construction and (the then prevailing) building codes as shown in Table 4 [28, 49].

⁵ Exact ranges determined in Section 3.0 using maximum likelihood estimation

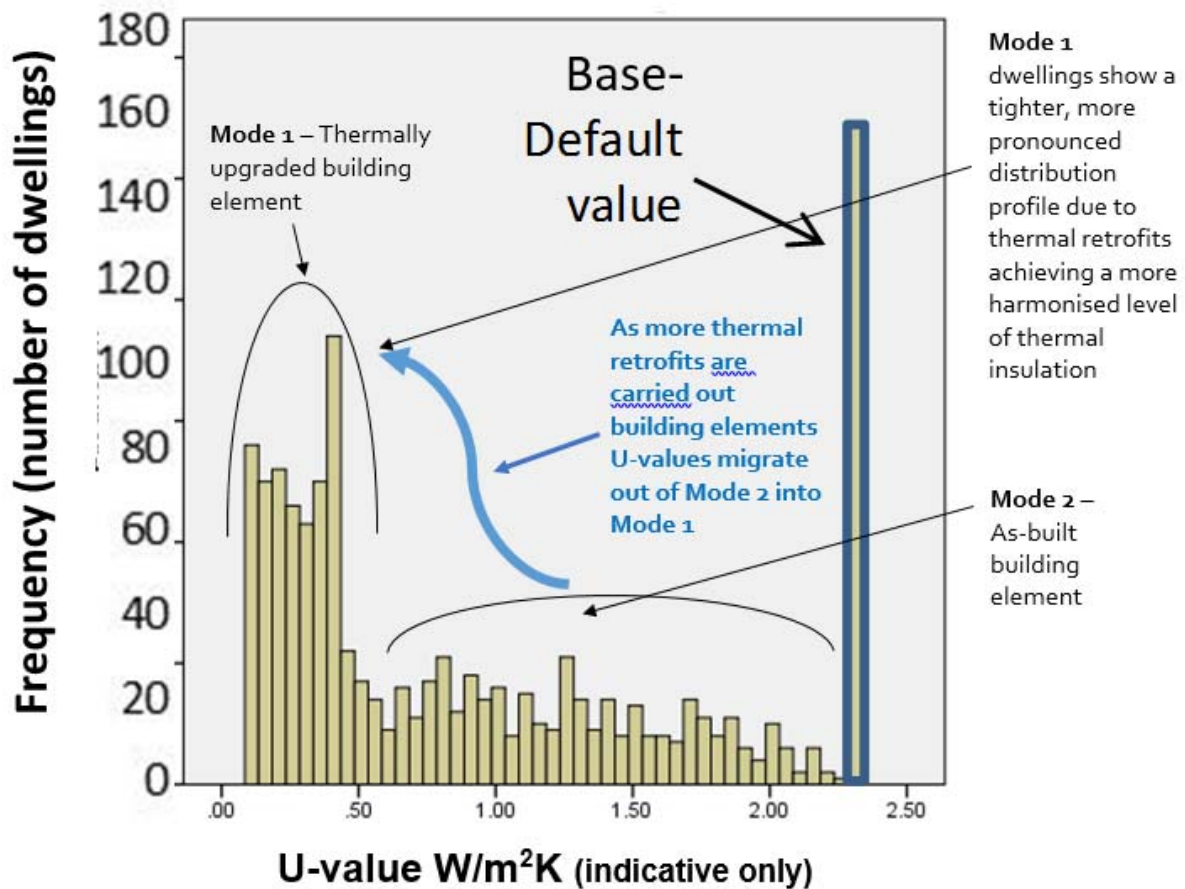
Table 4 Base-thermal-default U-values by period of thermal regulation in Ireland [50]

		Applicable Age Band	Base-default U-values (W/m ² K)		
			Roof	Wall	Floor
Date Regulation Introduced	N/A	<1978	2.3	2.1	1.2
	1976 (Draft)	1978-1982	0.4	1.1	0.6
	1981 (Draft)	1983-1993	0.4	0.6	0.6
	1991	1994-1999	0.35	0.55	0.45/0.6*
	1997	2000-2004	0.35	0.55	0.45/0.6*
	2002	2005-2006	0.25	0.37	0.37

* 0.45 = ground floor and 0.6 = exposed/semi-exposed floor

The frequency of default U-value selection across construction period, together with the independence of default U-value selection to building element type, implies that building assessors often select thermal-default U-values by period of construction, in preference to calculating actual elemental U-values. Current default U-Values in Ireland underrank 100 % of walls and 82 % of roofs [28]. As more retrofit interventions are carried out in the housing sector, current base-default U-values become less relevant to the real statistical distribution with the passage of time especially with respect to Mode 1 dwellings [19, 28]. The use of outmoded default U-values decreases the accuracy and hence credibility of both the EPC and the EPC database [28]. To eliminate the systemic error associated with outmoded base-thermal-default values [28], it is appropriate to remove base-default U-values from the database so the data then better meets accuracy, coherency, compatibly and clarity requirements [51].

Figure 4 Illustrative typical frequency distribution of wall and roof U-values [43]



2.3 Validation of EPC Dataset

A summary analysis of dwelling element U-value distributions by construction period is summarised in Figure 4 [19]. Thermally upgraded dwellings show a more pronounced distribution profile than dwellings yet to undergo significant thermal upgrades. Median U-values for upgraded dwellings are consistent with 2007 [52] and 2011 [53] Irish building regulations of 0.21 (2011) to 0.27 (2007) W/m^2K for walls, and 0.16 (2011) to 0.22 (2007) W/m^2K for roofs. Peaks observed consistently in distributions for upgraded dwellings relate to state-funded energy refurbishment grants to homeowners available through the SEAI [20] for walls that achieve a U-Value of 0.27 W/m^2K , and roofs that achieve U-values of 0.16 W/m^2K and 0.2 W/m^2K , for ceiling-level and rafter insulations respectively.

Data quality checks and measures taken to ensure final data quality corresponding to Eurostat validation levels ranging from 0 (lowest) to 5 (highest) are summarised in Table 5 [51, 54]. The data was checked for internal consistency to Eurostat validation level 1, intra-datasets time-series checks via differing periods of construction found data behaved consistently to validation level 2, while also confirming requirement to remove default U-values [19]. Using other data together with intra-domain consistency checks confirmed the quality of the data in the refined EPC dataset to data validation level 5 [51, 54].

Table 5 Summary of data quality checks and measures taken to validate EPC dataset [19]

		Description	Data provider	Action to check data was plausible
Valid- ation Level	1	File was compiled by an authorised authority	SEAI [55]	Review of SEAI audit and quality assurance mechanisms
	2	Intra-dataset time-series	Ahern [43]- Segmented dataset	Checks via differing time periods – data behaved consistently. Systemic error in the data established; default U-values (as described in Table 4) removed in the case of walls and roofs
		Defaults correlated with period of construction		
	5	Intra-domain consistency	Consistent with INSHQ dataset [56]	Check in respect of wall, roof and floor insulation levels
		Vernacular construction characteristics of dwelling thermal envelope established	INSHQ [56], TABULA [57, 58], CIBSE Guide A [59], literature [24, 30, 60-64]	Default U-values (as described in Table 4) removed as inconsistent with other data sources
				Data analysed to establish consistency with vernacular construction details and state-funded incentivised retrofit schemes

2.4 Maximum Likelihood Estimation of the parameters of the distribution

To ascertain the renovation status of the dwelling stock, mean U-values for refurbished (Mode 1) and as-built (Mode 2) dwellings by percentage of the dwelling stock applying were determined, by construction period as shown in Figure 5. The statistical relevance of the default U-values relative to the empirical distribution is discussed in other work [28]. Using maximum likelihood estimation a statistical model was developed. A generalised reduced gradient nonlinear solver

was used to determine maximum likelihood estimates for parameters for best-fit curves to empirical distributions of large datasets [40]. Figure 5 (b) shows how a best-fit normal⁶ distribution was fitted to the empirical data using constraints as set out in Table 6.

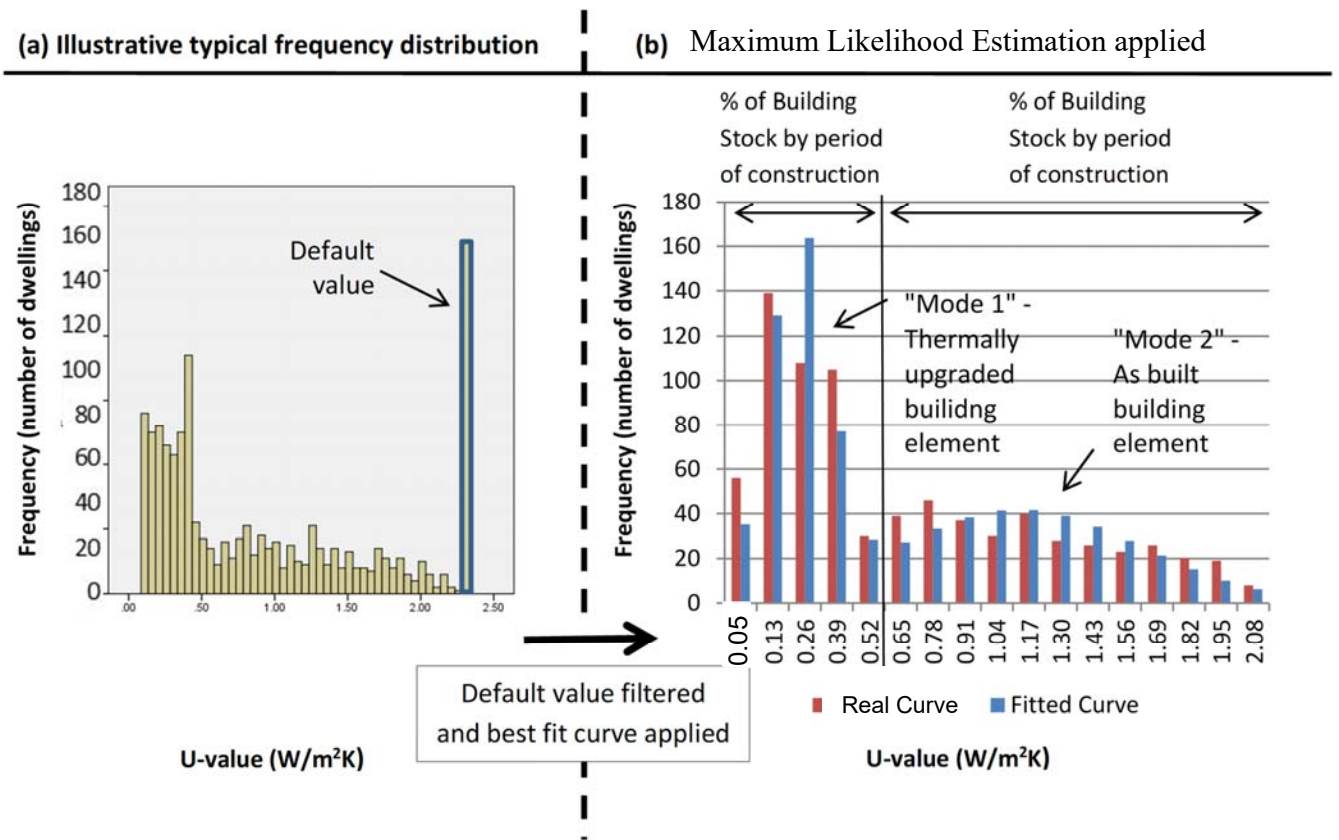
Table 6 Constraints used within the generalised reduced gradient nonlinear solver

Constraints	Mean 1	>=	0.1
	Standard Deviation 1	>=	0.01
	Mean 2	>=	Mean 1
	Standard Deviation 2	>=	0.01
	Proportion 1	<=	1 (100 %)
	Proportion 2	<=	0.1 (10 %)

The sum of the log of the likelihood values was used to avoid the products of the likelihoods being very small numbers leading to errors [45]. The maximum likelihood approach uses individual data points so is not dependent on the choice of histogram bin size. Histograms were employed to illustrate the goodness of fit [see Figure 5 (b) and typical methodology output shown in Figure 6].

⁶ The validity of selection of a normal curve is verified Section 3.0 and in detail in [19] C. Ahern, Introducing the default effect: reducing the gap between theoretical prediction and actual Energy consumed by dwellings through characterising data more representative of national dwelling stocks, Building Engineering, Technological University Dublin, 2019.

Figure 5 (a & b) Illustrative typical frequency distribution and analysis of wall and roof U-value [43]



3.0 Results & Analysis

Outputs from applying the statistical methodology ascribed to all single and two-storey dwellings by dwelling element type are presented Table 7. The validity of selection of a normal distribution to fit the empirical data was verified through evaluating the individual empirical U-values with fitted data points estimated by the maximum likelihood method [19]. Repeated data-splitting was used for internal validation of the model's performance [65]. Detached dwellings were isolated from the EPC dataset, rural detached dwellings were segmented, dwellings were hence classified by number of storeys, then by construction period (10 No.), followed by dwelling element i.e. wall, roof, and floor. The statistical model developed was applied repeatedly to each split dataset. The

robustness of the method was demonstrated [19] by consistent goodness-of-fit of the cumulative distribution function to the real data (see Figure 6 and Appendix C in [19]).

To externally validate the methodology, as shown in Figure 7, an independent sample for a different housing typology from the same population was isolated from the original EPC dataset [43]. The method is shown to be valid by the goodness-of-fit of the fitted curve to the real curve for a different housing typology [19]. The recommended defaults for walls and roofs for a different dwelling typology correlate with those recommended for the dwelling typology examined originally [19, 28]; corroborating the expectation that retrofit measures would be applied proportionately across all single-family dwellings.

The extent of thermal retrofits and thermal building regulation compliance for Ireland's predominant housing typology is presented in Table 7. The proportion of Mode 1 (retrofitted) and Mode 2 (as-built) dwellings by period of construction [reference Figure 5 (b)]; the mean U-values of Mode 1 and Mode 2 dwellings, referred to as 'Mean 1' and 'Mean 2'; and standard deviation of Mode 1 and Mode 2 dwellings are presented in Table 7 by dwelling element, by single and two-storey dwellings by construction period.

Referring to Table 7; mean roof U-values are generally lower than wall U-values, wall U-values range from 0.29 to 1.97 W/m²K for pre-thermal regulation dwellings and 0.28 to 0.7 W/m²K for post-thermal regulation dwellings; while roof U-values range from 0.13 to 1.18 W/m²K for pre-thermal regulation dwellings, and 0.13 to 0.96 W/m²K⁷ for post-thermal regulation dwellings. The improved thermal characteristic of roofs is attributable to the relative ease and lower cost of retrofitting attic insulation compared to wall insulation. Conversely however, as shown in Figure 8 and highlighted* in Table 7, there is a large proportion of post-thermal regulation roofs that do not comply with thermal building regulations. This may be attributable to lax adherence to building control measures during Ireland's housing construction boom between the mid-1990's and mid-2000's [66].

⁷ Max default for a post-thermal regulation dwellings roof is 0.49 W/m²K

Figure 6 Typical methodology output for one and two storey detached dwellings by period of construction (1967 – 1977)

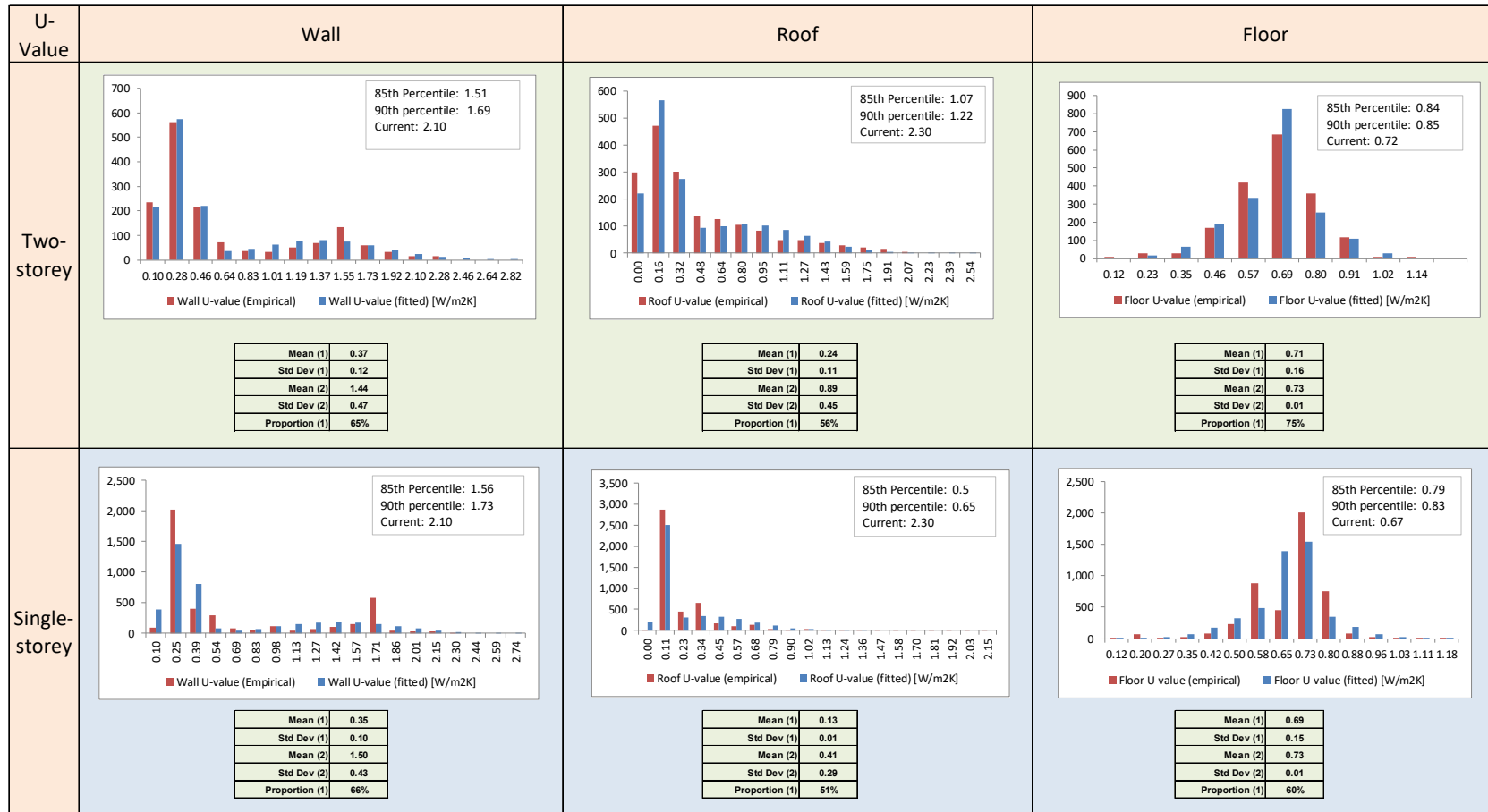


Figure 7 Methodology output for one and two storey dwelling semi-detached rural dwellings by period of construction (1967 – 1977)

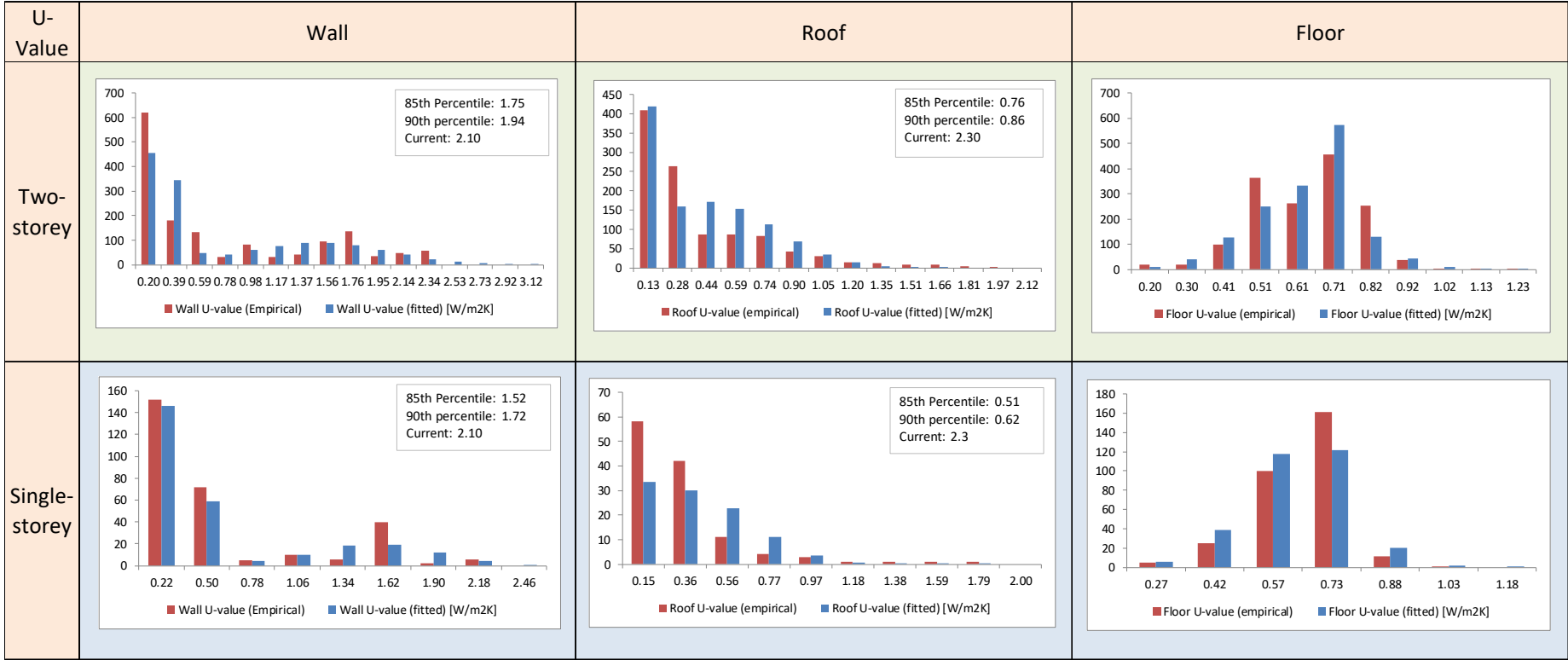
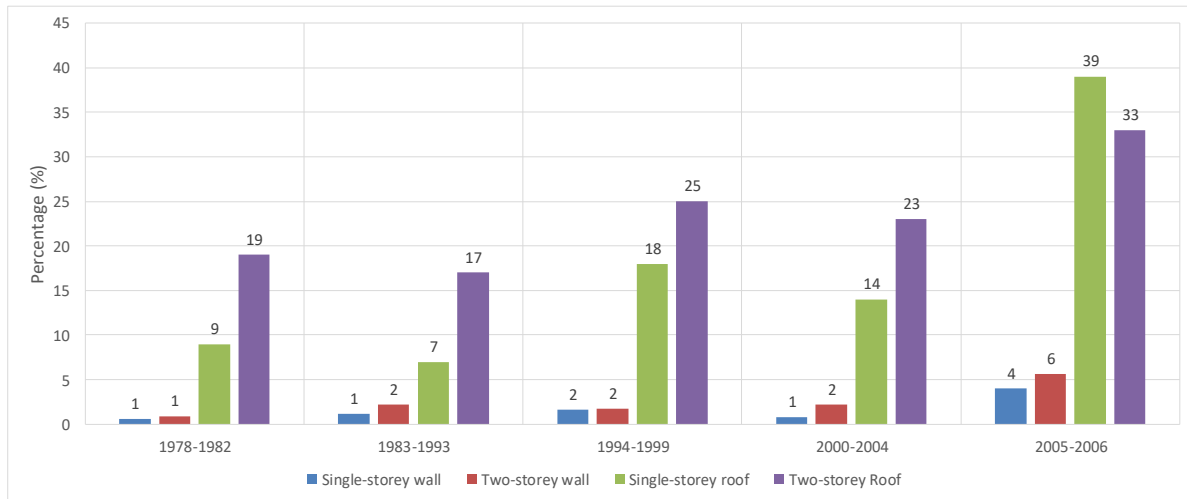


Figure 8 Percentage of dwelling walls and roofs non-compliant with prevailing thermal regulations



The mean U-values and standard deviation for Mode 1 (as-built) and Mode 2 (refurbished) dwellings by proportion of the dwelling stock applying by construction period shown in Table 7 are analysed in Table 8 to show the extent of thermal refurbishments of existing dwellings in Table 9. Referring to notes ‘a’ to ‘d’ indicated on Table 8:

- a. The relative scale of improvement from Mean 1 to Mean 2 in the thermal performance of pre-thermal regulation dwelling elements is more significant than in post-thermal regulation dwellings. For instance, an average of 70 % of dwelling walls constructed between 1967 and 1977, have been thermally refurbished to a U-value of circa 0.36 W/m²K (from 1.5 W/m²K) while 50 % of dwellings walls constructed between 1950 and 1966 have been thermally refurbished to a U-value of circa 0.32 W/m²K (from 1.3 W/m²K). The significant level of thermal refurbishments for these dwelling typologies may be attributable to these dwellings having the largest floor areas, relative to other pre-thermal regulation dwellings, but with low levels of insulation, meaning that these dwellings are considered to be the worst thermally performing dwelling types [24]. This may have provided greater motivation to the homeowner to carry out thermal refurbishments.
- b. In post thermal-regulation dwellings constructed between 1983 and 2006, a high proportion of Mode 1 dwelling elements represent the large number of dwellings that were constructed to better than prevailing thermal building regulations; for instance in two-

storey walls constructed between 2005 and 2006, the Mean 1 U-value is 0.29 W/m²K when default regulatory U-value is 0.37 W/m²K (see Table 4).

- c. The proportion of roofs constructed between 1978 and 2004 indicated as thermally refurbished is significantly lower than that indicated for two-storey roofs of the same construction period. This arises because the lower proportions associate with single storey roofs represent very significant retrofits (Mean 1 U-value ~ 0.13 W/m²K see Table 7), where the regulatory default U-value for the period is 0.25 W/m²K (see Table 4), meaning that 100 % of Mean 1 U-values are below the prevailing regulatory default U-values. The difference between single and two-storey dwellings might be attributed to the fact that roof surface area on a single-storey building impacts the dwelling heat loss to a much greater extent than in the equivalent two-storey dwelling.
- d. 70 % of pre-1900 two-storey walls while only 17 % of pre-1900 single-storey walls are indicated as “significantly” thermally retrofitted. In the case of two-storey walls, the large percentage returned by the methodology is explained by a more moderate reduction in U-values, from Mean 2 of 1.97 W/m²K to a Mean 1 of 1.13 W/m²K, compared to a reduction from a Mean 2 1.53 W/m²K to a Mean 1 0.39 W/m²K for single-storey walls.

Frequency weighted stock averages found 58 % of walls (U-value range from 0.29 to 0.39⁸ W/m²K) and 67 % (U value range from 0.13 to 0.29 W/m²K) of roofs to be significantly refurbished or upgraded in 2014. Mean U-values for walls and roofs in 2014 are shown in Table 10 along with comparable data in 2001 [24, 48, 56]. As the median level of thermal insulation behind the data quoted for 2001 in Table 10 is not expressly reported [24, 48, 56] it was not possible to determine an accurate mean U-value this data is thus presented for discussion purposes only. In Table 10, data for 2014 represents the results of this study. It is noted that the percentage of roof insulation installed appears to have reduced from 82 % to 64 % between 2001 and 2014; this arises as 82 % of roofs were insulated to a mean U-value of 1.3 W/m²K in 2001 whereas 67 % of roofs were insulated to a lower mean U-value of 0.37 W/m²K in 2014. Mean U-values achieved in 2014 are thus quoted for clarity; although it is noted, as illustrated by Figure 9, a significant thermal difference exists between pre and post-thermal regulation dwellings [19].

⁸ With the exception of two storey pre-1900 dwellings at 1.13 W/m²K

Table 7 Summary of statistical methodology outputs characterising dwelling envelope characteristics by period of construction

		Dwelling Envelope Element																	
		Wall				Roof				Floor				Windows					
		Single-storey		Two-storey		Single-storey		Two-storey		Single-storey		Two-storey		Single-storey		Two-storey			
		Mode 1	Mode 2	Mode 1	Mode 2	Mode 1	Mode 2	Mode 1	Mode 2	Mode 1	Mode 2	Mode 1	Mode 2	Mode 1	Mode 2	Mode 1	Mode 2		
Period of Construction	Pre-thermal building Regulations	>1900	% of the stock	17	83	70	30	56	44	49	51	17	83	94	6	71	29	75	25
			Mean	0.39	1.53	1.13	1.97	0.22	0.98	0.29	1.18	0.53	0.80	0.73	0.73	2.86	4.69	2.89	4.73
			Std. Dev	0.15	0.43	0.53	0.13	0.1	0.54	0.12	0.49	0.17	0.12	0.19	0.01	0.43	0.46	0.54	0.32
		1900-1929	% of the stock	15	85	15	85	27	73	52	48	10	90	94	6	56	44	59	41
			Mean	0.31	1.39	0.31	1.42	0.13	0.67	0.28	1.14	0.37	0.76	0.73	0.84	2.88	2.88	2.88	2.88
			Std. Dev	0.06	0.49	0.07	0.47	0.01	0.51	1.14	0.49	0.11	0.14	0.19	0.01	1.25	0.17	1.16	0.18
		1930-1949	% of the stock	19	81	30	70	27	73	59	41	10	90	85	15	44	56	42	58
			Mean	0.29	1.43	0.38	1.47	0.13	0.57	0.28	1.06	0.48	0.76	0.7	0.9	2.84	3.40	2.82	3.29
			Std. Dev	0.05	0.52	1.47	0.47	0.01	0.44	0.12	0.5	0.17	0.12	0.17	0.07	0.17	0.11	0.16	1.12
	1950-1966	% of the stock	41	59	42	58	36	64	59	41	82	18	88	12	29	71	28	72	
		Mean	0.31	1.26	0.33	1.3	0.13	0.49	0.25	0.99	0.72	0.73	0.7	0.73	2.76	3.29	2.76	3.2	
		Std. Dev	0.05	0.56	0.07	0.52	0.01	0.39	0.11	0.49	0.16	0.01	0.17	0.01	0.06	1.01	0.07	0.95	
	1967-1977	% of the stock	66	34	65	35	51	49	56	44	60	40	75	25	15	85	11	89	
		Mean	0.35	1.5	0.37	1.44	0.13	0.41	0.24	0.89	0.69	0.73	0.71	0.73	2.70	3.11	2.7	3.03	
		Std. Dev	0.1	0.43	0.12	0.47	0.01	0.29	0.11	0.45	0.15	0.01	0.16	0.01	0.01	0.83	0.01	0.74	
	Post-thermal building Regulations	1978-1982	% of the stock	54	46	57	43	52	48	95	5	45	55	13	87	51	49	52	48
			Mean	0.3	0.6	0.31	0.7	0.13	0.2	0.24	0.77	0.54	0.57	0.52	0.58	2.82	2.82	2.83	2.83
			Std. Dev	0.03	0.25	0.04	0.27	0.01	0.34	0.11	0.48	0.11	0.01	0.16	0.06	1.10	0.16	1.03	0.16
1983-1993		% of the stock	70	30	65	25	71	29	98	2	45	55	10	90	45	55	36	64	
		Mean	0.29	0.46	0.3	0.49	0.13	0.35	0.25	0.96	0.55	0.57	0.49	0.58	2.84	2.84	2.87	2.87	
		Std. Dev	0.46	0.17	0.03	0.18	0.01	0.32	0.12	0.58	0.11	0.01	0.16	0.06	1.04	0.17	0.94	0.18	
1994-1999		% of the stock	79	21	65	25	60	40	99	1	92	8	10	90	50	50	17	83	
		Mean	0.29	0.44	0.29	0.43	0.13	0.33	0.26	0.88	0.41	0.41	0.41	0.42	2.77	2.85	2.61	2.84	
		Std. Dev	0.02	0.22	0.02	0.14	0.01	0.23	0.1	0.48	0.02	0.13	0.11	0.02	0.05	0.46	0.6	0.16	
2000-2004	% of the stock	75	25	63	27	49	51	99	1	38	62	25	75	44	54	46	54		
	Mean	0.29	0.39	0.29	0.43	0.13	0.31	0.26	0.96	0.39	0.41	0.4	0.42	2.63	2.74	2.59	2.75		
	Std. Dev	0.02	0.16	0.02	0.14	0.01	0.23	0.09	0.5	0.06	0.01	0.08	0.02	0.48	0.06	0.47	0.06		
2005-2006	% of the stock	93	7	94	6	84	16*	98	2	45	55	39	61	63	37	66	34		
	Mean	0.28	0.48	0.29	0.49	0.19	0.46	0.22	0.71	0.32	0.34	0.34	0.34	2.06	2.75	2.08	2.73		
	Std. Dev	0.03	0.33	0.05	0.2	0.05	0.39	0.07	0.47	0.06	0.01	0.01	0.05	0.19	0.19	0.18	0.12		

* Non thermal-regulation compliant dwelling roofs – reference Figure 7

Table 8 Percentage of walls and roofs which have been significantly or very significantly thermally retrofitted and/or upgraded by period of construction [43]

		Period of Construction	Pre-thermal regulation	Walls			Roofs			
				% Mode 1 dwellings		Frequency weighted average	% Mode 1 dwellings		Frequency weighted average	
				single-storey	two-storey		single-storey	two-storey		
Period of Construction	Pre-thermal regulation	< 1900	17%	70% ^a	49%	56%	49%	52%	50%	
		1900-1929	15%	31%	25%	27%	52%	42%		
		1930-1949	19%	30%	24%	27%	59%	47%		
		1950-1966	50%	49%	50% ^a	36%	59%	50%		
		1967-1977	72%	66%	70%	51%	56%	54%		
	Post-thermal regulation	1978-1982	54%	57%	55%	52% ^c	95%	78%	84%	
		1983-1993	70%	65%	68% ^b	71%	98%	87%		
		1994-1999	79%	65%	72%	60%	99%	84%		
		2000-2004	75%	63%	68%	49%	99%	80%		
		2005-2006	93%	94%	94%	84%	98%	93%		
			Average across dwelling stock			58%	Average across dwelling stock			67%

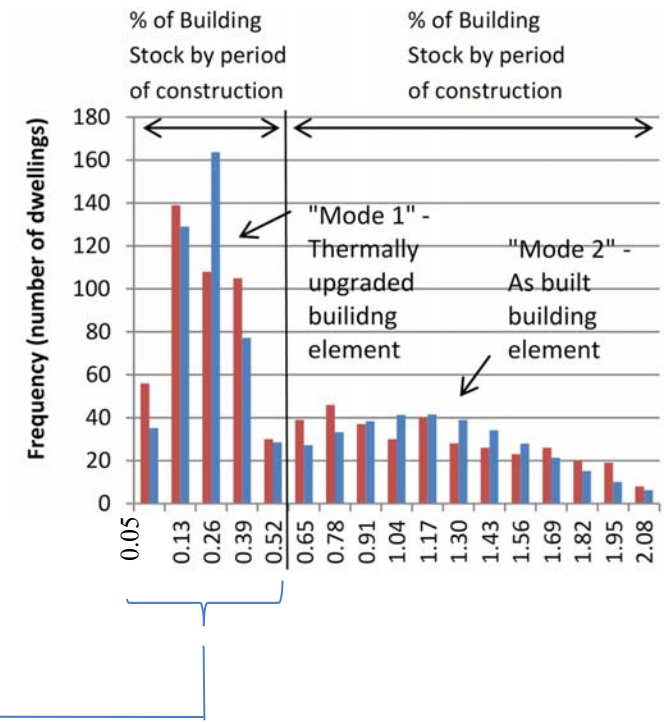


Table 9 Extent of thermal refurbishment of existing dwellings

				Proportion refurbished (%)	U-Value (W/m ² K)
Construction period	Before thermal building regulations	Building Element	Walls	46	0.29 to 0.39*
			Roofs	50	0.13 to 0.29
	After thermal building regulations		Walls	70	0.28 to 0.31
			Roofs	84	0.13 to 0.26

* With the exception of two storey pre-1900 dwellings at 1.13 W/m²K

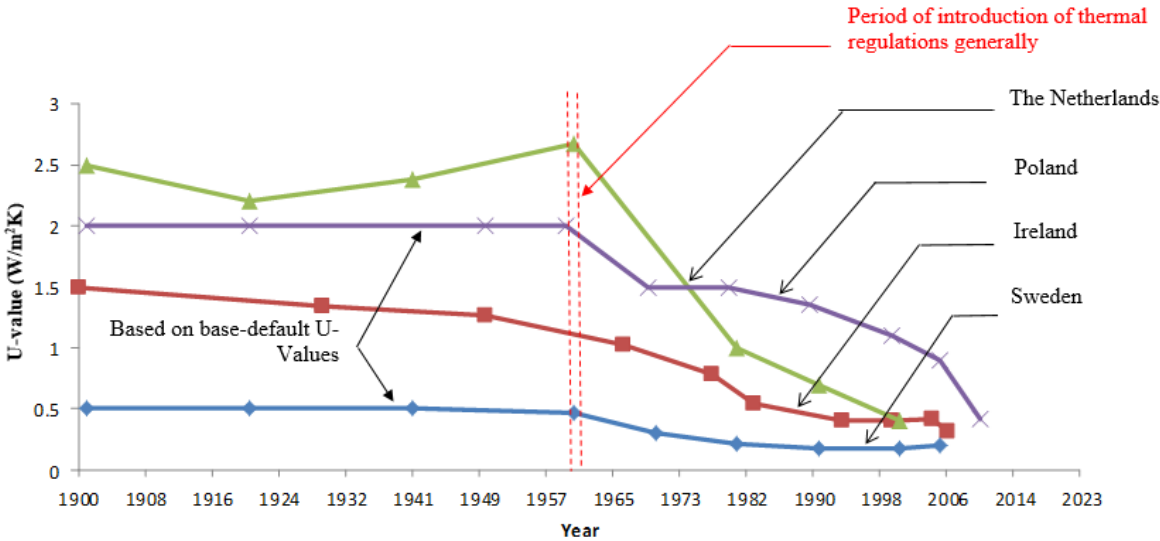
Levels of insulation in floors are difficult to identify retrospectively, consequently, floor U-values are based typically on base-default U-values.

Figure 9 compares the average wall U-values by construction period for detached housing in Ireland [43] with available data for Sweden, the Netherlands and Poland [41] which includes all dwelling typologies, is not as contemporaneous as the data for Ireland, and is based on base-thermal defaults. Figure 9 shows the data for Ireland to compare favourably with the data for Netherlands and Poland.

Table 10 Penetration of significant thermal upgrades in the detached Irish housing sector over time [43, 56]

Year of Survey		Walls		Roof		Double-glazed windows		Floor		Source
		%	Mean U-value (W/m ² K)	%	Mean U-value (W/m ² K)	%	Mean U-value (W/m ² K)	%	Mean U-value (W/m ² K)	
Year of Survey	2001	56	1.01	82	1.3	61	-	25 ^f	0.6	Ahern et al. (2013) [22] and INSHQ 2001-2002 [50] ^f Healy and Clinch 2004 [44]
	2014	58	0.66	67	0.37	97	2.92	53	0.59	This research

Figure 9 U-values for external walls in different countries [41, 43]



4.0 Limitations of this study

4.1 Dataset Quality

The EPC database [43] presents a favourable characterisation of the dwelling stock because homeowners applying for grants are obliged to have an EPC. 20.3 % of dwellings contained in the EPC database examined were because of their sale, 4 % from a private letting and 75.7 % were certified for “unknown” reasons. SEAI publish grant scheme statistics [18] however the data was not classified by dwelling type but by individual measures which include heating and renewable energy upgrades. The national statistics relating to upgrades of dwelling envelopes for *all* dwelling typologies in the Irish housing sector, consistent with the EPC database, are shown in Table 11.

Table 11 State-granted fabric energy-efficiency measures in the Irish housing sector for all dwelling typologies (rural and urban) by July 2014 [18]

Measures	Number of dwellings completed
Roof Insulation	112,992
Cavity	99,753
Dry-Lining Insulation	9,865
External Insulation	12,170
Total	234,780

From the data in Table 11 it cannot be ascertained if a particular household undertook several measures simultaneously. However it is (i) unlikely that homeowners carried out external *and* cavity insulation or wall insulation without also installing roof insulation, and (b) likely that homeowner’s carried-out roof insulation separately or dry-lining *along with* cavity or external insulation. On this basis, the total number of refurbished dwellings in the database is conservatively estimated at 112,992. The total number of dwellings in Ireland at the time of the 2011 census was 1,658,243. 8.6% of homeowners who availed of state-led grant schemes to upgrade the thermal fabric of their dwelling by July 2014. This is consistent with the 193,432 of dwellings that were awarded grants under schemes by Oct 2016. The EPC database consisted 463,582 dwellings. The estimated percentage of state-granted thermally refurbished dwellings in the database was thus 24 %; reduced from 50 % in 2010 [58].

Dwelling assessors are required to act with integrity and diligence to ensure that each assessment is executed competently while dwelling parameters are calibrated to an extent through dwelling audits (see Table 5), notwithstanding the dataset may be influenced by assessors who may not always carry out thermal assessments of the dwelling envelope rigorously [19, 28].

4.2 Database refinement

Maximum likelihood estimation was used to fit a bi-modal normal curve to the empirical data. As shown in Figures 10 and 11, the fitted curve is an approximating function intended to capture important patterns in the data while discarding noise and discrete localised peaks.

The approximating function creates synthetically average data with the assumption that data does not contain small-scale structures.

Figure 10 Typical relationship of empirical to fitted frequency distribution for a dwelling element (1900 – 1929)

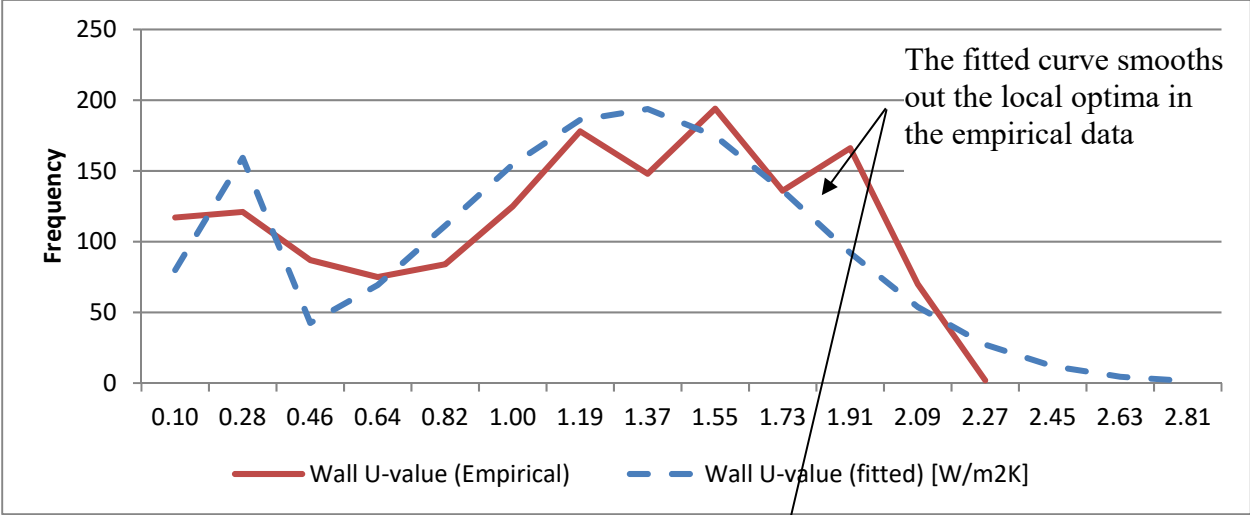
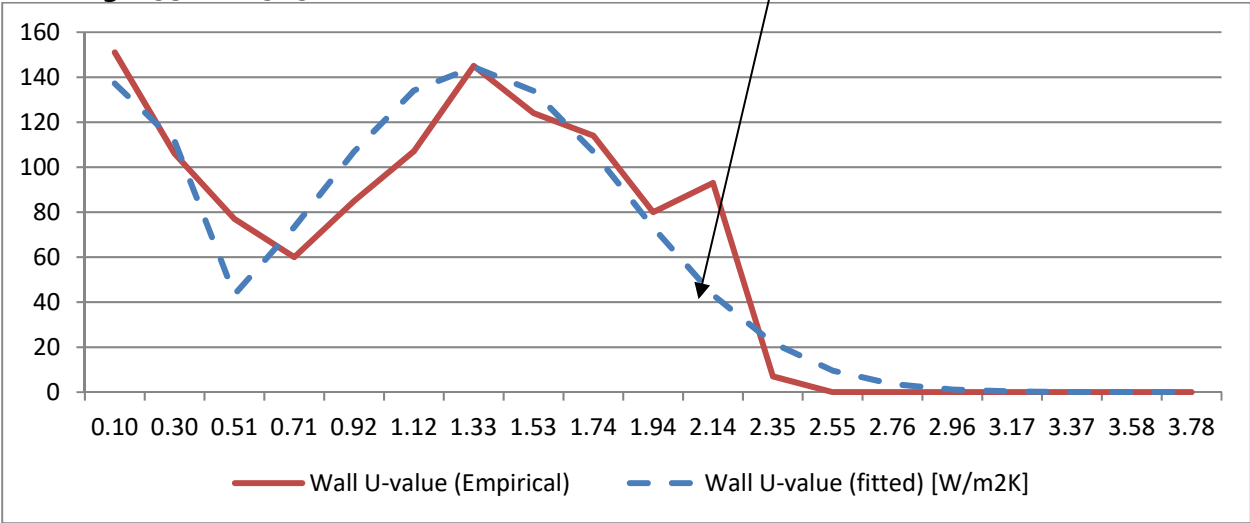


Figure 11 Typical relationship of empirical to fitted frequency distribution for a dwelling (1930 to 1949)



4.3 Model Output

Outputs from the model are renovation activity as shown in Table 7. Table 7 lists U-values applicable to detached dwellings only. Assuming retrofit measures are applied proportionately across the stock these figures are supposed indicative of the renovation status of the pre-2006 Irish dwelling-stock at large.

5.0 Conclusions

It has been found that in existing dwellings 58 % of walls (U-value range from 0.29 Wm²K to 0.39 Wm²K) and 67 % (U-value range from 0.13 Wm²K to 0.29 Wm²K) of roofs had significant levels of retrofitted thermal insulation. The (i) extent of thermal retrofits and (ii) high degree of energy-efficiency improvements in Ireland contribute significantly to; a) household energy usage per square metre being 20 % below the UK average and 9 % below the EU 27 average in 2010, and b) the average energy efficiency of Irish housing having improved by 34 % between 1995 and 2011 (2.5 % per annum). The extent of thermal upgrades means the;

- a) distinctions between the thermal efficiency of pre-thermal regulation and post-regulation dwellings, whilst still valid, is lessening,
- b) association between dwelling age and energy efficiency is diminishing as more retrofits are carried out,
- c) often-made assumption that the majority of dwellings in Ireland are thermally sub-standard is no longer valid.
- d) use of pessimistic ‘as-built’ default U-values in energy performance assessments is outmoded.

While the state fund grant schemes have been successful in encouraging homeowners to carry out energy efficiency works the majority of savings to have come from lower cost, more accessible measures such as roof and cavity wall insulation. Research by Sustainable Energy Authority of Ireland forecasts the opportunity for a further 9,400GWh of energy saving potential in the Irish residential sector in the period 2021-30 [24]. However, these savings need to come from deeper measures such as external wall insulation, internal dry-lining installation and floor insulation together with low carbon heating systems.

5.0 References

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