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Energy Performance Certification: Misassessment Due to Assuming Default Heat Losses

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Abstract: Energy Performance Certificates (EPCs) are issued when dwellings are constructed, sold or leased in the EU. Where the cost of obtaining the required data is prohibitive, EPC assessors use nationally applicable default-values. To ensure that dwellings are not assigned a wrongly-higher EPC rating, a standardised thermal bridging transmittance coefficient (Y-value) is typically adopted for all existing dwellings while worst-case overall heat loss coefficients (U-values) are used. Default U-values are applied to a specific building element type (roof, wall, floor etc.) based on building codes and regulations applicable at time of construction. Due to significant building fabric upgrades, default U-values are considerably higher than real U-values. This constitutes a systematic 'default effect' error typical of large national EPC datasets. For the dataset considered thermal default use overestimates potential primary energy savings from upgrading by 22% in dwellings constructed when thermal building regulation applied and by 70% in dwellings built before thermal building regulations. A methodology has been developed that derives from an EPC dataset, a method for calculating a realistic energy-improvement payback when use of pessimistic default U-values is unavoidable.

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Repository: Mendeley Data
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Title

Energy Performance Certification: Misassessment due to assuming default heat losses.

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Highlights

1. Use of thermal default values in EPCs over-estimates benefits of energy-led refurbishments.
2. Use potentially overestimates energy consumption by 22% in post-building regulation dwellings.
3. Use potentially overestimates energy consumption by 70% in pre-building regulation dwellings.
4. A payback calculation for energy refurbishment is derived for use when thermal default use is unavoidable.

Abstract –

Energy Performance Certificates (EPCs) are issued when dwellings are constructed, sold or leased in the EU. Where the cost of obtaining the required data is prohibitive, EPC assessors use nationally applicable default-values. To ensure that dwellings are not assigned a wrongly-higher EPC rating, a standardised thermal bridging transmittance coefficient (Y-value) is typically adopted for all existing dwellings while worst-case overall heat loss coefficients (U-values) are used. Default U-values are applied to a specific building element type (roof, wall, floor etc.) based on building codes and regulations applicable at time of construction. Due to significant building fabric upgrades, default U-values are considerably higher than real U-values. This constitutes a systematic 'default effect' error typical of large national EPC datasets. For the dataset considered thermal default use overestimates potential primary energy savings from upgrading by 22% in dwellings constructed when thermal building regulation applied and by 70% in dwellings built before thermal building regulations. A methodology has been developed that derives from an EPC dataset, a method for calculating a realistic energy-improvement payback when use of pessimistic default U-values is unavoidable.

Keywords Default Effect, Prebound Effect, Default U-values, Energy Performance Gap, Thermal Energy Peformance Gap, Energy Performance Certification, Detached Dwellings, Irish Housing Stock, Building Energy Rating

List of abbreviations

1S	Single Storey
2S	Two Storey
CAO	Central Statistics Office
DEAP	Dwelling Energy Assessment Procedure
DHW	Domestic Hot Water
EPBD	European Performance of Buildings Directive
EPC	Energy Performance Certificate
EU-27/28	Total EU member countries as of time of publication of referenced work
RB	Reference Building

RD	Reference Dwelling
SAP	Standard Assessment Procedure (UK)
SEAI	Sustainable Energy Authority of Ireland (formerly Sustainable Energy Ireland - SEI)
SyAv	Synthetically Average
TABULA	Typology Approach for Building Stock Energy Assessment
U-value	Overall heat transfer coefficient (W/m^2K)
Y-value	Thermal bridging transmittance coefficient (W/m^2K)

1.0 Introduction

Households consume 27% of end-use energy in the EU 28 (Eurostat, 2016). The extent and duration of the dominance of the thermal characteristics of pre-existing houses on this energy use depends on construction rates, floor areas and specifications of new dwellings (Simpson et al., 2016). Average replacement rates for existing housing stocks in the European Union (EU) are less than 0.1% (Bell, 2004) so the majority of Europe's existing dwellings will remain in 2050 (Visscher et al., 2016). In the United Kingdom, for example, around 75% of dwellings that will exist in 2050 have already been constructed (Ravetz, 2008). Achieving lower energy use and associated greenhouse gas emissions thus requires energy refurbishment of these existing dwellings; together with greater efficiency and harnessing renewable technologies in the generation of energy supplied to houses (Kohler and Hassler, 2002; Lowe, 2007; Roberts, 2008; Schaefer et al., 2000; Simpson et al., 2016; Weiss et al., 2012).

Knowledge about cost-effective energy-saving measures can encourage behaviour that reduces household energy costs (Gram-Hanssen et al., 2007; Tuominen and Klobut, 2009). The Energy Performance of Building Directive (EPBD) [Directive 2002/91/EC] drives policy to accelerate reducing energy consumption in European building stocks (Majcen et al., 2013a). The EPBD mandates comparable Energy Performance Certificates (EPCs) for buildings constructed, sold or leased across the European Union (EU) (EU, 2002a, b). An EPC is accompanied by an Advisory

Report that recommends energy efficiency improvements feasible from both technical and economical perspectives (Pérez-Lombard et al., 2009; SEAI, 2013; Stein and Meier, 2000). However even economically advantageous recommendations are not always adopted (Christensen et al., 2014; Gram-Hanssen et al., 2007; Tuominen and Klobut, 2009). One barrier is that homeowners anticipate financial savings smaller than estimated in the Advisory Report (Gram-Hanssen, 2014), undermining the credibility of the report. To overcome this barrier, the estimated reduction in energy consumption from a specific energy-saving intervention in a particular dwelling as given by the EPC, should reflect the actual decrease in energy consumption (EU, 2002b; Majcen et al., 2013a; Majcen et al., 2013b).

1.1 Energy Performance Certification

Energy classification of dwellings differs across the EU Member States (MSs) (Arcipowska et al., 2014; Arkesteijn and van Dijk, 2010; BPIE, 2010; Pérez-Lombard et al., 2009). In Ireland (SEAI, 2012b) and in the UK (SAP, 2012) this classification is based on calculated annual delivered and primary energy consumptions together with carbon dioxide emissions for standardised occupancy. The procedure balances energy required for space heating, ventilation, water heating and lighting with energy generated by building integrated photovoltaic and solar thermal systems. An EPC:

- Presents a calculated building's energy performance rating on a scale of A (which should have the lowest fuel bills) to G (Pérez-Lombard et al., 2009).
- Uses the same A-to-G scale to rate a dwelling's greenhouse gas emissions.

National EPC methodologies need to have:

- Credibility and accuracy, so that, for a given climate, buildings with better ratings use less energy (Pérez-Lombard et al., 2009; Sousa et al., 2017; Stein and Meier, 2000).
- Balance applicability to a wide variety of buildings with lack of specificity to each single building (Arkesteijn and van Dijk, 2010).

- Clarity that enables users to understand a) the overall result and b) the effect of improvement choices on the EPC (Arkesteijn and van Dijk, 2010; Stein and Meier, 2000).
- Reproducibility, so that for a specific building the method used gives the same result independent of the assessor (Arkesteijn and van Dijk, 2010; Pérez-Lombard et al., 2009).
- Transparency that ensures energy ratings are consistent (Arkesteijn and van Dijk, 2010; Pérez-Lombard et al., 2009; Stein and Meier, 2000).
- Cost-effectiveness by avoiding labour intensive data acquisition (Arkesteijn and van Dijk, 2010), and poorly user-interfaced or complex simulation programs that require extensive training (Pérez-Lombard et al., 2008).

Trade-offs between reproducibility, accuracy, assessor expertise and costs are necessary (BPIE, 2010). During an EPC assessment, where accurate building data acquisition would be excessively labour-intensive and/or invasive, national specified default values are used by an assessor. Default values are normally pessimistic to (Arkesteijn and van Dijk, 2010);

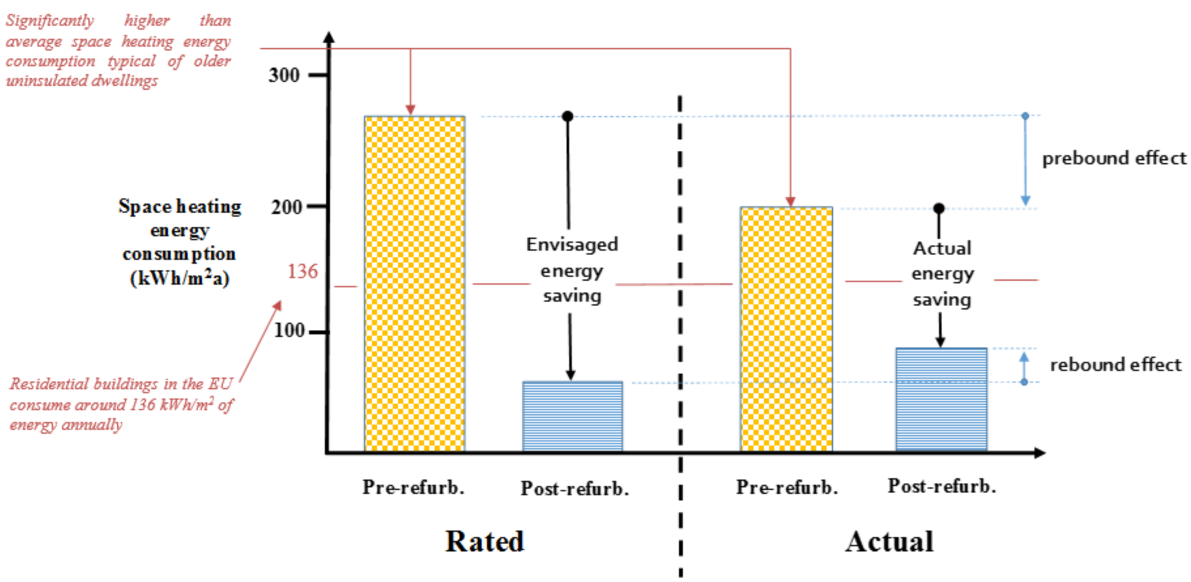
- avoid a better-than-merited energy rating,
- enable homeowners to know the energy advantage of carrying-out upgrading retrofits,
- encourage homeowners to record energy upgrades that inform EPCs, and
- propel assessors to seek-out information to provide an accurate energy rating.

Input data based on worst-case default values (Hull et al., 2009; Majcen et al., 2013b; Míguez et al., 2006; Pérez-Lombard et al., 2009; SEAI, 2013; Stein and Meier, 2000; Sunikka-Blank and Galvin, 2012; Yohanis et al., 2008) for thermal envelope characteristics, external temperatures, internal loads, system efficiencies and occupancy patterns together with specified 'standard' conditions leads to discrepancies, as shown in Fig. 1, between EPC-rated predicted and measured (Sunikka-Blank and Galvin, 2012) domestic energy consumptions (Cozza et al.; Gram-Hanssen, 2014; Majcen et al., 2013b; Pérez-Lombard et al., 2009).

As shown in Fig. 1, space heating energy consumption above 136 $kWh/m^2/a$ is typical of less energy-efficient, older, un-refurbished dwellings (Lapillonne et al., 2012a; Simpson et al., 2016). The 67% of European housing built prior to 1980 (Norris and Shiels, 2004) predate the introduction of meaningful thermal building regulations to housing. In the absence of empirical data, default 'as-built' overall thermal transmittance coefficients (U-values) of dwelling envelopes across Europe (*inter alia* Austria, Ireland, Italy, Poland, Spain, Sweden and the UK) are determined by (Ahern, 2019; Arcipowska et al., 2014; BPIE, 2010; Rasooli et al., 2016; van den Brom et al., 2017);

- whether a roof, wall or floor is being considered,
- for pre-thermal regulation dwellings, the date of construction,
- for post-thermal regulation dwellings, prevailing applicable draft building regulations.

Fig. 1 How the prebound and rebound effects may limit energy saving to be less than envisaged[1] (Sunikka-Blank and Galvin, 2012)



The characteristics of older dwellings are often less readily documented than for those constructed recently (Rasooli et al., 2016; Skea, 2012) leading to default values being employed (Ahern, 2019; Arkesteijn and van Dijk, 2010) . As shown in Table 1, use of default values may lead the projected EPC to predict higher than realisable energy refurbishment improvements (Ahern, 2019; Ahern et al., 2016; Arkesteijn and van Dijk, 2010; Majcen et al., 2013b; van den Brom et al., 2017), particularly for older pre-refurbishment dwellings (Arkesteijn and van Dijk, 2010; Cozza et al.). For this 'prebound effect', illustrated in Fig. 1, theoretical predicted energy

[1] Actual values based on measured values [see Ref Sunikka-Blank, M., Galvin, R., 2012. Introducing the prebound effect: the gap between performance and actual energy consumption. Building Research & Information 40, 260-273.]

consumption is overestimated in average and less energy-efficient dwellings (i.e. space heating consumption of 136 kWh/m^2/a or greater) (Majcen et al., 2013b) with occupants consuming 30% less heating energy on average than predicted by the EPC (Sunikka-Blank and Galvin, 2012).

Predicted energy use can also be underestimated in new or retrofitted dwellings that should have a space heating consumption of 100 kWh/m^2/a or less; as shown in Fig. 1. This is explained partly by a ‘rebound effect’ (Berkhout et al., 2000) that ensues because in thermally-upgraded dwellings, higher internal comfort temperatures are more affordable leading energy consumption to increase by 10 to 35% (Galvin and Sunikka-Blank, 2016) rather than reduce (Clinch and Healy, 1999; Clinch and Healy, 2003; Cozza et al.; Druckman et al., 2011; Herring, 2006; Lomas, 2010; Majcen et al., 2013b). As illustrated by Table 1, prebound and rebound effects lead to energy savings significantly less than envisaged.

As sub-optimal or partial refurbishments can render future energy performance improvements more difficult or expensive (Sandberg et al., 2016), the EPBD requires refurbishments are assessed against cost-optimal criterion to (EuroACE, 2013; Simpson et al., 2016);

i) ensure coherent and well-planned refurbishment standards that avoid low-cost but sub-optimal improvements, and
ii) invest in interventions that will recoup their life-cycle costs.

Rather than calculate the cost-optimal interventions for every single building, EPBD guidelines (EU, 2012b) require a set of reference buildings (RBs) for each EU member state representative of typical national or regional building stocks (Ahern et al., 2016; Ballarini et al., 2014; Corgnati et al., 2013). RBs can be used to produce overall energy saving extrapolations for the total building stock (Ahern et al., 2016; Ballarini et al., 2014; EU, 2012a; Ferrari et al., 2019).

Thermal refurbishments of Irish housing have resulted in 58% of walls and 67% of roofs having significant levels of insulation in 2014 (Ahern and Norton, 2019b), this has led to; (i) less association between a dwelling’s age and its energy efficiency, and (ii) currently-used default U-values being outmoded. Pessimistic as-built default U-values under-rank the energy performance of circa 90% of dwellings, under-ranking 100% of walls and 82% of roofs (Ahern, 2019; Ahern et al., 2016). Under-ranking pre-regulation dwellings contributes to the prebound effect (Ahern and Norton, 2019a; Ahern et al., 2016). Procedures used in Ireland (Ahern et al., 2013; Badurek et al., 2012) along with those in Italy (Loga et al., 2010), Spain (Iortega, 2011) and Austria (Amtmann, 2010) use stock-aggregation methodologies to calculate overall national residential stock energy consumption using as-built or base-default U-values applied to equally default dwelling typologies classified by construction period.

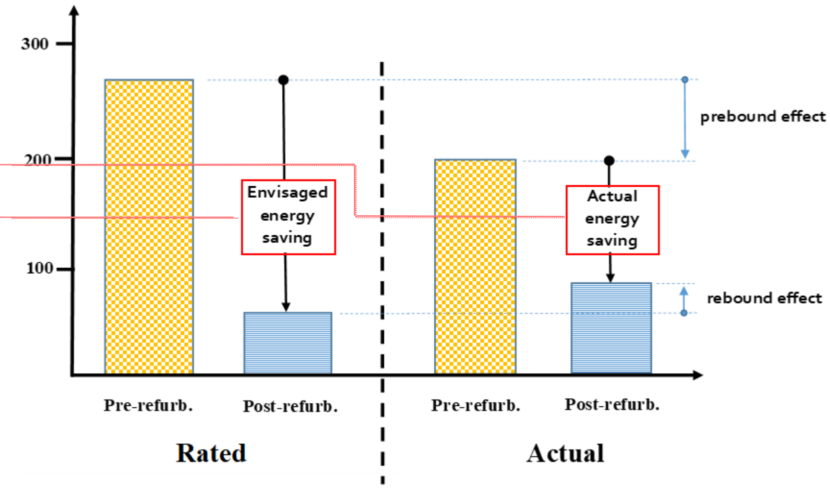
In the 27 EU member states in 2009 (EU 27), space heating consumed 68% of energy used in the residential sector, accounting for 210 million tonnes of oil equivalent (Mtoe) or 244.23 TWh (Lapillonne et al., 2012b). Of the overall heat lost from dwellings 80 to 90% is by heat transfer through the building fabric; 8 to 16% is through air infiltration and 4 to 16% is through thermal bridges (Ahern, 2019; Ahern and Norton, 2019a).

Thermal bridges, with a significantly higher thermal conductivity than is average in the dwelling (Cash, 1997), occur because of (i) geometry (e.g. a corner,) (ii) structural requirements (e.g., lintels, foundation, party wall, wall ties etc.), and (iii) construction practice (e.g. no edge insulation in ground floor). Thermal bridges are classified as; a) repeating, b) non-repeating c) random (Xtratherm, 2014). A Y-value describes the sum of all the non-repeating thermal bridging heat transfer coefficients (H_{TB}) divided by the total exposed area of the building envelope (A_{exp}), and is expressed as W/m^2K. A Y-value is added to an average U-value to account for the thermal bridges (Xtratherm, 2014). A singular standardarised Y-value, not relevant to the building type (Little and Arregi, 2011), typically adopted in EPC methodologies for all existing dwellings (SEAI, 2012a), overestimates (Andrews, 2011; Little and Arregi, 2011) or underestimates (Pittam and O’Sullivan, 2017) heat loss due to thermal bridging so must be calculated.

In Ireland (SEAI, 2016a) and in the UK (DCLG_UK, 2013) publicly-available EPC methodologies are used to calculate the energy classification of dwellings. Ireland has an established, regulated and publically available EPC database (Arcipowska et al., 2014). In the Irish housing stock, the percentage of dwellings constructed before the mid 1970’s, before building regulations required increased levels of thermal insulation (CSO, 2006; SEAI, 2012b), mirror European housing stocks generally (Norris and Shiels, 2004). The motivation of this work is to examine the Irish EPC dataset to quantify the potential overestimation of energy-led refurbishments from use of pessimistic default U-values and standardised Y-values.

Table 1 Illustration of how use of default use results in unrealistically short payback periods (Arkesteijn and van Dijk, 2010)

		Pessimistic default employed?	Energy Performance Rating	Payback period for thermal upgrade measures
Building Certification Information available?	Yes	No	High	Realistic
	No	Yes	Low	Unrealistically short



2.0 Methodology

34% of the EU 28 population lived in detached houses in 2013 (Eurostat, 2015). Ireland's predominant house typology, comprising 18% of the total dwelling stock are rural detached, oil-heated dwellings (Ahern et al., 2016). This dwelling typology is adopted as a case study Reference Dwelling (RD) as while Ireland has the highest proportion of single family dwellings in Europe (Economidou et al., 2011), countries such as the UK, Greece, Norway and the Netherlands have similar profiles (see Fig. 2)

EPCs in Ireland are generated through the "Dwelling Energy Assessment Procedure" (DEAP) software administered by the Sustainable Energy Authority of Ireland (SEAI). SEAI made the detailed national empirical EPC dataset publicly available in 2014 (SEAI, 2014). 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 (Ahern and Norton, 2019a), as shown in Table 2 and elucidated in Table 3, to describe the single-family detached dwelling stock through 35 number Synthetical Average[2] (SyAv) default-free RDs representative of the Irish national building stock (Ahern et al., 2016; Ballarini et al., 2014; Corgnati et al., 2013).

Thermal default use was compared with empirically-derived thermal envelope data for their effect on the EPC rating of dwellings. A representative selection set of four pre and post thermal regulations largely default-free RDs [2 x single storey (1S) and 2 x two storey (2S)], totalling eight RDs, were selected from Table 2 for input to the Irish national EPC methodology, DEAP. As highlighted in Table 2, RDs representing the highest quantity of dwellings (N) were selected as detailed in Table 5. The selection set represents 206,183 dwellings accounting for 50.7% of national detached dwellings in Ireland (see Table 5).

Energy use for the SyAv RDs were calculated using DEAP, employing EPC data in Tables 2 and 3. The energy use for the SyAv RDs were hence recalculated assuming;

[2] Based on the statistical analysis of a large building sample the "Synthetical Average Building" (*SyAv*) approach identifies an "archetype" defined as "a statistical composite of the features found within a category of buildings in the stock" IEA_ECBCS, 2004. Stock Aggregation, Methods for the evaluation the environmental performance of building stocks, in Annex 31 - Energy-related environmental impact of buildings, in: IEA-ECBCS (Ed.). International Initiative for a Sustainable Built Environment (iiSBE, Ontario, Canada.

(i) national default U-values by period of construction[3] (see Table 4), and

(ii) the standard national thermal bridging default Y-value of 0.15 W/m^{2}K.

iii) a randomly-selected, north-east/south-west (NE/SW) orientation,

iv) double-glazed windows with 10% frame area,

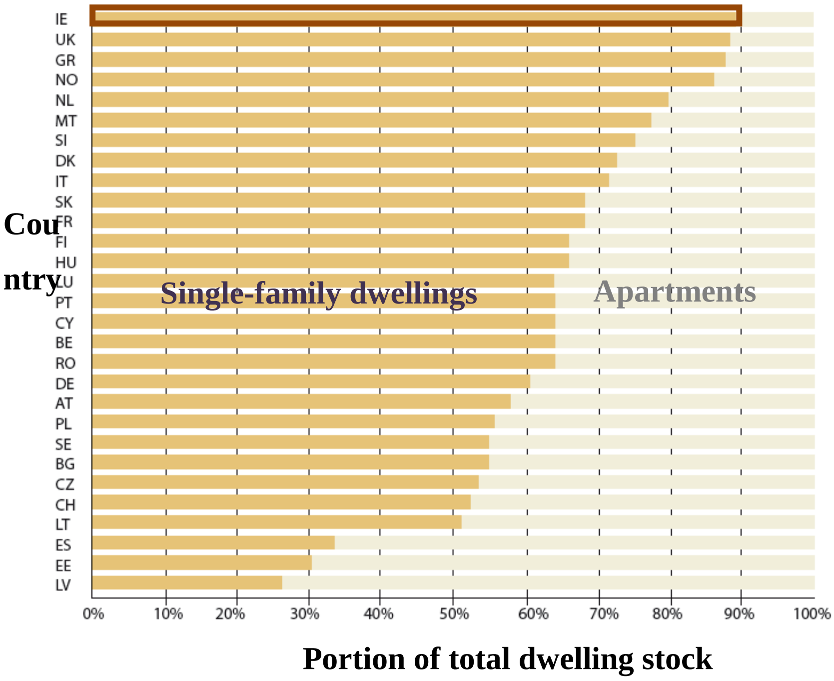
v) 300 litre DHW calorifier with cylinder thermostat,

vi) no incandescent lightbulbs,

vii) 21^{o}C living room temperature,

viii) no sides of the dwelling were sheltered.

Fig. 2 Distribution of single-family and apartment buildings in Europe (Economidou et al., 2011)



[3] Categorisations in Table 3 span across traditional periods of construction used by Irelands national calculation methodology, DEAP – construction periods with highest frequency of dwellings within a category were selected for default comparison (see Table 5) and Section 4.2.4 in [39] for more detail

Table 2 Empirical default free characterisation of single (1S) and two-storey (2S) reference dwellings depicting Ireland's predominant housing typology (Ahern and Norton, 2019a)

					Heat loss through building fabric						Geometry											System	
					Thermal transmittance; U-Value (W/m^2K)						Area (m^2)					Height (m)		%	(m^3)	Surf. Area/Vol.		Heating fuel source	
	Category	x	Quantity (N)		Window	Floor	Roof	Wall	Thermal bridging; Y-value (W/m^2K)	Air permeability ($m^3/(h.m^2)$)	Wall	Roof	Floor	Window	Door	Ground floor height	First floor height	Window Ratio	Volume	Compactness of Building Envelope	Occupancy	Oil	Solid Fuel
Post-thermal Regulation	1S,	1	105616	5839	2.06	0.33	0.19	0.28	0.08	10	153	150	149	27	3.74	2.57	N/A	18%	382.93	1.26	3.19	75%	16%
		2		26266	2.72	0.40	0.13	0.29	0.09	10	110	134	133	25	3.54	2.53	N/A	23%	336	1.2	3.47	75%	19%
		3		10519	2.78	0.4	0.33	0.29	0.09	10	111	135	134	25	3.57	2.53	N/A	23%	340	1.2	3.42	75%	16%
		4		10819	2.79	0.41	0.33	0.42	0.09	10	110	135	133	25	3.56	2.53	N/A	23%	338	1.2	3.44	74%	18%
		5		33542	2.83	0.55	0.13	0.29	0.09	10	102	126	127	25	3.21	2.52	N/A	25%	320	1.2	3.51	75%	18%
		6		335	2.84	0.57	0.13	0.46	0.09	10	102	126	126	24	3.19	2.52	N/A	24%	318	1.2	3.62	68%	27%
		7		9730	2.84	0.57	0.35	0.46	0.09	10	102	126	126	24	3.19	2.52	N/A	24%	318	1.2	3.62	68%	27%
		8		8566	2.82	0.57	0.2	0.6	0.10	10	102	127	128	26	3.25	2.53	N/A	26%	324	1.19	3.25	69%	26%
Pre-thermal Regulation		9	103245	11264	2.73	0.71	0.13	0.39	0.09	13.07	102	111	111	22	3.2	2.58	N/A	21%	285	1.22	2.72	66%	29%
		10		13973	3.13	0.69	0.13	0.4	0.09	12.21	101	119	119	24	3.2	2.54	N/A	24%	302	1.21	2.85	69%	26%
		11		10219	3.16	0.71	0.43	0.39	0.09	12.57	101	116	116	23	3.2	2.56	N/A	23%	295	1.22	2.80	68%	27%
		12		20164	3.2	0.73	0.45	1.6	0.09	13.03	102	112	111	22	3.2	2.58	N/A	21%	286	1.22	2.73	70%	25%
		13		3007	2.86	0.43	0.13	0.3	0.09	14.02	100	95	95	15	3.06	2.59	N/A	15%	246	1.25	2.51	59%	34%
		14		2165	2.85	0.76	0.13	0.29	0.09	14.75	100	95	95	15	3.1	2.59	N/A	15%	248	1.25	2.52	58%	34%
		15		2947	2.86	0.76	0.13	1.41	0.09	13.79	100	95	95	14	3.03	2.58	N/A	14%	246	1.25	2.51	59%	33%
		16		12696	2.87	0.76	0.65	1.4	0.09	12.89	100	94	94	14	2.96	2.58	N/A	14%	244	1.26	2.50	59%	33%
		17		9255	3.4	0.76	0.57	1.43	0.09	12	100	96	96	15	3.2	2.6	N/A	15%	250	1.24	2.53	58%	35%
		18		2984	2.89	0.53	0.22	0.15	0.09	12	104	95	94	14	2.87	2.6	N/A	13%	244	1.27	2.49	59%	31%
		19		6847	2.89	0.8	0.22	0.53	0.09	12	104	95	94	14	2.87	2.6	N/A	13%	244	1.27	2.49	59%	31%
		20		2633	2.89	0.8	0.98	0.53	0.09	12	104	95	94	14	2.87	2.6	N/A	13%	244	1.27	2.49	59%	31%
		21		5091	4.93	0.8	0.98	0.53	0.09	12	104	95	94	14	2.87	2.6	N/A	13%	244	1.27	2.49	59%	31%
Post-thermal Regulation	2S,	1	104813	8344	2.08	0.34	0.22	0.29	0.08	10.00	173	129	118	34	3.96	2.55	N/A	20%	564	0.81	3.19	75%	16%
		2		21596	2.62	0.40	0.25	0.29	0.09	10.00	160	131	115	32	3.85	2.54	2.04	20%	528	0.84	3.34	74%	17%
		3		28377	2.81	0.47	0.26	0.45	0.09	10.00	155	131	115	32	3.67	2.53	1.99	21%	520	0.84	3.50	72%	21%
		4		1329	2.81	0.47	0.90	0.47	0.09	10.00	157	130	116	33	3.69	2.53	2.02	21%	527	0.83	3.47	72%	21%
		5		40353	2.84	0.51	0.25	0.30	0.09	10.00	152	129	115	33	3.56	2.52	1.98	21%	519	0.84	3.53	71%	24%
		6		4814	2.83	0.52	0.24	0.71	0.09	10.00	152	126	116	34	3.51	2.51	2.03	22%	527	0.82	3.25	69%	23%
Pre-thermal Regulation		7	93243.71	26778	2.92	0.71	0.26	0.37	0.09	13.13	154	110	102	29	3.42	2.53	2.16	19%	480	0.84	2.66	64%	30%
		8		1770	3.03	0.71	0.89	0.41	0.09	12.00	153	123	116	36	3.39	2.54	2.13	23%	542	0.80	2.88	70%	25%
		9		15848	3.17	0.74	0.98	1.56	0.09	14.06	153	111	103	30	3.36	2.55	2.16	19%	486	0.83	2.68	63%	31%
		10		23511	2.94	0.72	0.28	1.27	0.08	12.88	168	105	98	24	3.68	2.54	2.31	15%	476	0.84	2.50	65%	29%
		11		2728	2.89	0.73	1.18	1.97	0.08	14.00	179	110	103	25	3.82	2.56	2.37	14%	508	0.83	2.49	59%	31%
		12		10084	2.88	0.74	1.14	1.42	0.08	14.25	157	96	89	21	3.65	2.46	2.24	14%	418	0.88	2.49	62%	32%
		13		5718	2.89	0.73	1.18	1.13	0.08	12.00	179	110	103	25	3.82	2.56	2.37	14%	508	0.83	2.49	59%	31%
		14		6807	4.73	0.73	1.18	1.97	0.08	12.00	179	110	103	25	3.82	2.56	2.37	14%	508	0.83	2.49	59%	31%

Table 3 Summary reference dwelling report complying with EU Commission Delegated Regulation 244/2012

		Quantity	Description and/or source
Primary energy conversion factors	electricity	2.19	(SEAI, 2016b, 2017)
Carbon emission factors	electricity ($kgCO_2/kWh$)	0.473	(Ahern, 2019; SEAI, 2016b, 2017)
	Oil (kerosene) ($kgCO_2/kWh$)	0.257	
	Coal ($kgCO_2/kWh$)	0.341	
Climatic conditions	location	Mullingar, Ireland	
	heating degree-days	2,389	Mullingar Weather Station - degree days below 15.5°C (occupied and unoccupied period) (Eireann, 2017)
	weather file	IWEC2 file	(Ahern, 2019)
	terrain	Rural	Nearby buildings not accounted for.
Geometry	length x width x height (m^3)	Varies	See Table 2 Related to the heated/conditioned air volume.
	number of floors		See Table 2
	S/V (surface-to-volume) ratio (m^2/m^3)		
	ratio of window area over total building envelope area (%)		
Orientation		N, S, E, W, NE, NW, SE, SW	(Ahern, 2019)
Internal gains	use	Single-family houses	According to the building categories proposed in Annex 1 to Directive 2010/31/EU
	average thermal gain per occupant (W/m^2/occupant)	93	CIBSE Guide A (CIBSE, 2006)
	delivered lighting energy($kWh/m^2/yr$)	1,149	EPC database (Ahern, 2014)

Table 3 (cont.) Summary reference dwelling report (cont.) complying with EU Commission Delegated Regulation 244/2012

<table>
<tr><th colspan="3"></th><th>Quantity</th><th>Source and/or description</th></tr>
<tr><td rowspan="14">Building Elements</td><td rowspan="3">average U-value (W/m²K)</td><td>wall</td><td colspan="2" rowspan="3">See Table 2</td></tr>
<tr><td>roof</td></tr>
<tr><td>window</td></tr>
<tr><td colspan="2">living area as a % of total floor area</td><td>16</td><td>EPC database (Ahern, 2014)</td></tr>
<tr><td rowspan="2">thermal bridges</td><td>total length (m)</td><td colspan="2" rowspan="2">See Table 2</td></tr>
<tr><td>average linear thermal transmittance (W/mK)</td></tr>
<tr><td rowspan="2">thermal mass factors</td><td>Utilisation (J/m²K)</td><td>200</td><td rowspan="2">See Section 4.2.3.4 in (Ahern, 2019)</td></tr>
<tr><td>Intermittent heating (J/m²K)</td><td>111</td></tr>
<tr><td colspan="2">type of shading systems</td><td>Curtains</td><td></td></tr>
<tr><td colspan="2">average g-value of glazing</td><td>0.76</td><td>Wood/PVC Double 6mm air-filled glazing average U-value 3.1 W/m²K (Ref: Table S9 DEAP (SEAI, 2012b))</td></tr>
<tr><td colspan="2">Windows Draught Stripped (%)</td><td>94</td><td>(Ahern, 2014)</td></tr>
<tr><td colspan="2">infiltration rate [(m³/(hm²) at 50Pa]</td><td colspan="2">See Table 2</td></tr>
</table>

Table 4 Default U-values by period of building regulation in Ireland (SEAI, 2017)

		Applicable Age Band	Default U-values (W/m^2K)		
			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

3.0 Results

For dwellings with a NE/SW orientation primary energy consumption associated with both primary and secondary heating systems increased by 31% for post-thermal regulation dwellings and 92% for pre-thermal regulation dwellings when default U-values and a standardised Y-value is assumed. As shown in Table 6, thermal default use was found to (i) increase the total rated primary energy consumption of the dwelling by 22% in post-thermal regulation dwellings and 70% in pre-thermal regulation dwellings, and (ii) increase CO_2 emissions by a corresponding 23% in post thermal regulation dwellings and 72% in pre-thermal regulation dwellings. As illustrated by Fig. 3 and detailed in Table 5, use of thermal default U-values and a standardised Y-value will result in a significantly lower-than-merited energy rating, particularly for pre-thermal regulation dwellings.

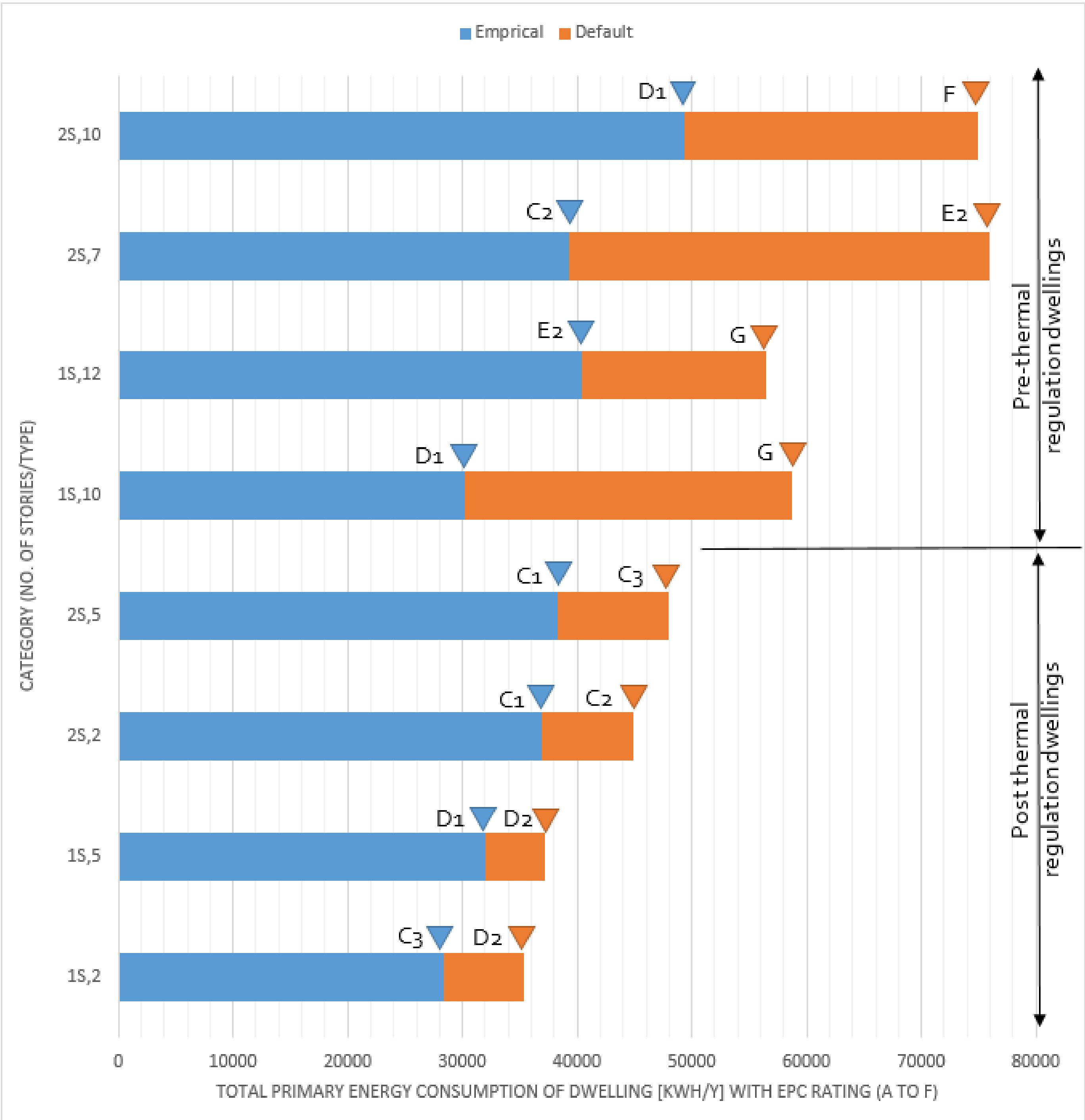
Table 5 Summary of DEAP methodology outputs for selected empirical ‘E’ and default ‘D’ reference dwellings

				Primary Energy [kWh/y]											CO_2 Emissions [kg/y]					
	Category from Table 2	Quanity (N)	Period of Construction	Main space heating system		Secondary space heating system		Main water htg. sys.	Pumps & Fans	Energy for lghtingg	Total		per m^2 of floor area		Total		per m^2 of floor area		EPC Rating	
				E	D	E	D	E/D	E/D	E/D	E	D	E	D	E	D	E	D	E	D
Post thermal regulation	1S,2	26266	2000-2004	16777	22516	3439	4610	5972	541	1708	28436	35347	213.81	265.77	7221	9033	54.29	67.92	C3	D2
	1S,5	33542	1983-1993	19951	24263	4086	4966	5845	541	1626	32049	37240	252.35	293.23	8175	9537	64.37	75.09	D1	D2
	2S,2	21596	2000-2004	21268	27905	4355	5710	7709	541	3012	36885	44877	160.37	195.12	9325	11420	40.54	49.65	C1	C2
	2S,5	40353	1983-1993	22468	30480	4600	6235	7709	541	3007	38325	47971	166.63	208.57	9703	12232	42.19	53.18	C1	C3
Pre thermal regulation	1S,10	13973	1967-1977	18584	42324	3807	8652	5671	541	1520	30124	58709	253.14	493.35	7680	15176	64.54	127.53	D1	G
	1S,12	20164	1950-1966	27401	40746	5607	8330	5493	541	1420	40461	56530	364.52	509.28	10400	14614	93.69	131.65	E2	G
	2S,7	26778	1967-1977	23837	54297	4879	11096	7303	541	2668	39228	75905	192.3	972.08	9968	19585	48.86	96.01	C2	E2
	2S,10	23511	Before 1900	32432	53636	6633	10961	7170	541	2600	49375	74907	251.91	382.18	12635	19330	64.46	98.62	D1	F
		206183																		

Table 6 Summary of DEAP methodology outputs for selected empirical 'E' and default 'D' reference dwellings

				Primary Energy [kWh/y]								CO_2 Emissions [kg/y]			
				Space Heating System				Total				Total			
	Category from Table 2	Quanity (N)	Period of Construction	E	D	Increase	Average Increase pre and post regulation	E	D	Increase	Average Increase pre and post regulation	E	D	Increase	Average Increase pre and post regulation
Post thermal regulation	1S,2	26266	2000-2004	20216	27126	34%	31%	28436	35347	24%	22%	7221	9033	25%	23%
	1S,5	33542	1983-1993	24037	29229	22%		32049	37240	16%		8175	9537	17%	
	2S,2	21596	2000-2004	25623	33615	31%		36885	44877	22%		9325	11420	22%	
	2S,5	40353	1983-1993	27068	36715	36%		38325	47971	25%		9703	12232	26%	
Pre thermal regulation	1S,10	13973	1967-1977	22391	50976	128%	92%	30124	58709	95%	70%	7680	15176	98%	72%
	1S,12	20164	1950-1966	33008	49076	49%		40461	56530	40%		10400	14614	41%	
	2S,7	26778	1967-1977	28716	65393	128%		39228	75905	93%		9968	19585	96%	
	2S,10	23511	Before 1900	39065	64597	65%		49375	74907	52%		12635	19330	53%	

Fig. 3 Total primary energy consumption and associated energy rating for selected empirical and default reference dwellings as calculated by the DEAP methodology



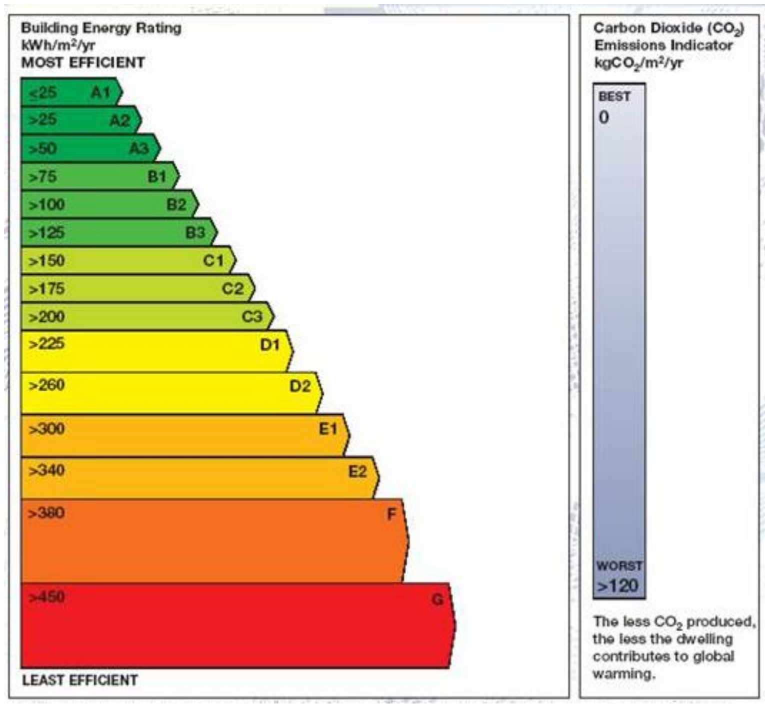
4.0 Discussion

EPCs are the most prominent source of information on the energy performance of the EU's building stock (Arcipowska et al., 2014) influencing property renovation and purchasing decisions (Charalambides et al., 2019). Use of thermal default U-values and a standardised Y-value results in significantly increased rated primary energy consumption and CO_2 emissions attributable to dwellings compared with energy consumption calculated using empirical EPC data (Ahern, 2019).

Pre-thermal regulation as-built default U-values assume no thermal insulation of the dwelling envelope (Ahern, 2019). The use of pessimistic thermal defaults combined with the reality of significant thermal upgrading of pre-thermal regulation dwellings has led to significantly higher rated primary energy consumption (average of 92% when compared to empirical data) associated with the space heating system. This results in a 70% increase in rated primary energy associated with the dwelling with a corresponding 72% predicted increase in rated CO_2 emissions produced.

Fig. 4 illustrates the energy ratings for EPCs in Ireland. At the less energy efficient end of the scale (D1 to G), the range between ratings is more significant than at the more efficient of the scale (A1 to C3). Referring to Table 5 and Fig. 3, the label attributed to the pre-regulation dwellings employing defaults ranges from 3 to 5 ratings lower that if empirical information was used. This is particularly remarkable as this phenomenon occurs at the lower end of the rating scale (D1 to G) where the range between ratings is at its greatest.

Fig. 4 Energy Performance Certification (Building Energy Rating) labels in Ireland



As default U-values for post-regulation dwellings are calculated assuming thermal insulation to be present, the discrepancy in calculated rated primary energy associated with the heating system as shown in Table 6, at an average of 31%, while less than that of post-thermal regulation dwellings is still significant. This leads to a 22% increase in rated primary energy associated with the dwelling with a corresponding 23% predicted increase in rated CO_2 emissions. As in the case of pre-thermal regulation dwellings there is a corresponding increase in the energy-rating label when empirical data is used, ranging from 1 to 2 ratings between the C1 and D2 ratings (see Fig.4).

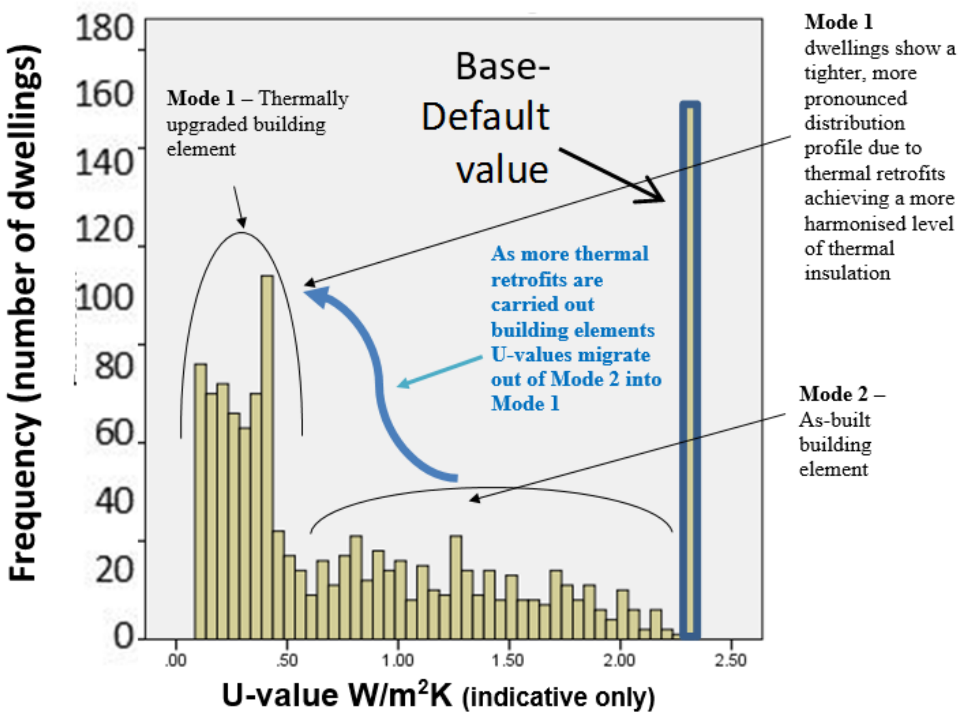
Use of thermal defaults therefore results in a significantly lower than merited energy rating, particularly for pre-thermal regulation dwellings.

5.0 Stochastically-based EPC payback calculation

Extracted from the Irish national EPC dataset (Ahern, 2014) , a typical frequency distribution for dwelling wall and roof U-values by construction period shows the thermal characteristics to be bi-modally distributed. Referring to Fig. 5:

- ‘Mode 2’ building elements are walls and roofs as constructed with original U-values of 0.6 to 2.3 W/m^{2}K.
- ‘Mode 1’ dwellings are thermally-upgraded building elements with lower U-values ranging between 0.1 to 0.59 W/m^{2}K.
- As more thermal upgrades are completed, more building elements U-values will fall within Mode 2 than Mode 1.
- The standard deviation for Mode 2 is greater than that of Mode 1 demonstrating that retrofits harmonise levels of thermal insulation.
- There are statistically anomalous spikes 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 relating to default U-value selection (Ahern, 2019; Ahern et al., 2016). The frequency of selection across construction periods, together with default U-value selection being independent to building element type, implies that building assessors often select base-default U-values by construction period rather than calculating actual elemental U-values.

Fig. 5 Illustrative typical frequency distribution of wall and roof U-values (Ahern, 2019)



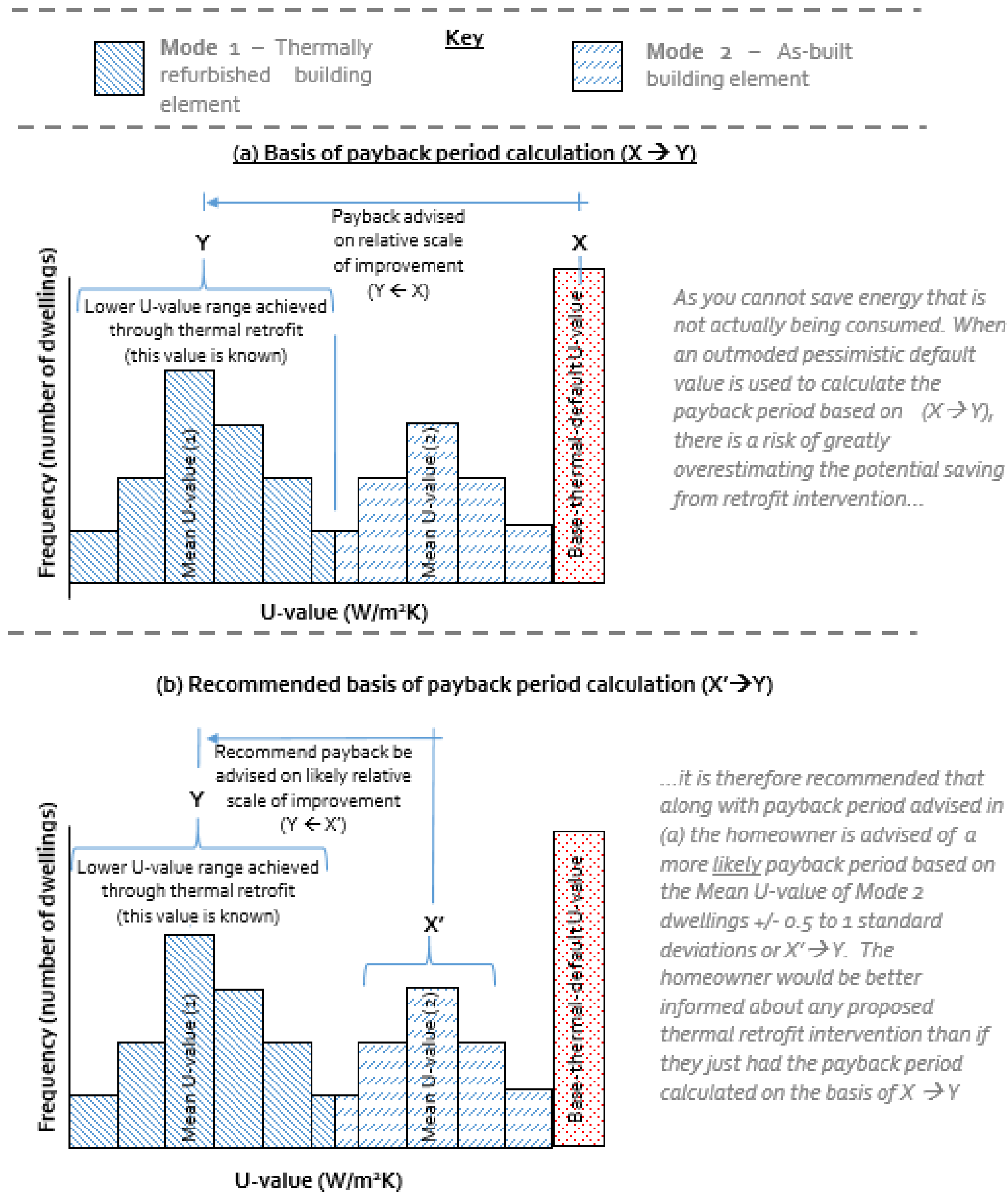
Payback periods, when thermal-defaults are employed are calculated as shown in Fig.6 (a). Referring to Fig.6 (a):

- When carrying out an estimation of the payback realisable through retrofit interventions, the desired retrofit U-values to be achieved occurs statistically, around the mean of Mode 1 dwellings, denoted (Y). The value for (Y) is thus known.
- Default U-values by period of construction, denoted (X), are employed where the wall U-value is “unknown”.
- Shorter than realisable payback periods result from the unrealistic scale of improvement from the assumed pessimistic default U-values (X) to the refurbished U-values (Y).

Accordingly, it is recommended that where default U-values have been employed in a payback calculation that a more likely, stochastically based payback period, as described in Fig.6 (b) is also offered to the homeowner. Referring to Fig.6 (b):

- Mean ‘Mode 2’ U-values, denoted (X’), by period of construction can be established by using maximum likelihood estimation of the parameters of the distribution (described in detail in (Ahern et al., 2016)).
- It is recommended that these statistically derived (X’) values replace the pessimistic default (X) value in the payback calculation to offer a more likely payback period to the homeowner.

Fig. 6 (a & b) Basis and recommendation for payback period calculation arising from thermal refurbishments when base-default U-values are used



6.0 Limitations of this study

The EPC database employed (Ahern, 2014) to characterise the default-free empirical RDs may present a favourable characterisation of the dwelling stock as homeowners must obtain an EPC to qualify for a state-led grant schemes. The estimated percentage of state-grant aided thermally refurbished dwellings in the database is 24% (Ahern, 2019; Ahern and Norton, 2019a); reduced from 50% in 2010 (Badurek et al., 2012). Where information within the database was found to be questionable or unreliable, the composition of the reference dwelling was informed instead through other available data and expert enquiries. Thus the quality of the characterisation relies on subjective expert judgment (Heo et al., 2012). Due to lack of information on the composition of dwelling stocks, this has been a common approach (Ahern et al., 2013; Corgnati et al., 2013; EU, 2012a; Heo et al., 2012; Loga et al., 2016; Mata et al., 2014). To facilitate a comparison the calculations for theoretical predicted energy consumption are carried out at a singular orientation. It is likely that the values will change at different orientations.

7.0 Recommendations

To enable a more informed retrofitting strategies; reports of the assessor should;

- highlight how building element U-values were determined,
- state how accurate they estimate those values to be, and
- carry-out a sensitivity analysis highlighting the impact their assumptions may have on the energy label and/or potential energy savings resulting from thermal upgrades.

Alternatively, homeowners could be offered the more likely, stochastically based, payback period for the refurbishment works, described in Section 5.

8.0 Conclusions

Using (i) Ireland's predominant single-family housing typology as a case study dwelling, (ii) a transparent generalisable methodology to create a stock model from a large empirical Energy Performance Certification (EPC) database, employing default-free reference dwellings (RDs) was defined in (Ahern and Norton, 2019a) using a 'bottom-up' approach. Using the RD's created in (Ahern and Norton, 2019a) this research quantifies the overestimation of calculated rated energy use of dwellings characteristed by thermal default U-values and standardised Y-values compared with calculated energy use of dwellings characterised by empirical U-values and calculated Y-values.

Use of pessimistic thermal default U-values and standardised Y-values significantly increases rated primary energy consumption and CO_2 emissions attributable to a dwelling when compared with a rating calculated using empirical data. Use of thermal defaults over estimates the total rated primary dwelling energy consumption by 22% in post-thermal regulation dwellings and 70% in pre-thermal regulation dwellings. The associated overestimation in rated CO_2 emissions at 23% in post thermal regulation dwellings and 72% in pre-thermal regulation dwellings, mirrors primary rated energy consumption figures. Use of thermal defaults therefore results in a significantly lower-than-merited energy rating, particularly for pre-thermal regulation dwellings.

Where pessimistic default thermal transmittance values are necessarily employed, this work recommends a more appropriate method of payback calculation, use of the method will help narrow the energy performance gap by increasing the accuracy and hence credibility of the EPC and its associated advisory report so enabling investment in energy efficiency for the residential sector.

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***Declaration of Interest Statement**

Declaration of interests

√ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

√ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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