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Author(s)	Moran, Paul;Hajdukiewicz, Magdalena;Goggins, Jamie
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Understanding the complexities of building physics and human behaviour in achieving a nearly zero energy building

[1, 2, 3] P. Moran, [1, 2, 3] M. Hajdukiewicz & [1, 2, 3, 4] J. Goggins

[1]*College of Engineering & Informatics, National University of Ireland, Galway, Ireland.*

[2]*Ryan Institute for Environmental, Marine and Energy Research, National University of Ireland, Galway, Ireland.*

[3]*Informatics Research Unit for Sustainable Engineering (IRUSE), Department of Civil Engineering, National University of Ireland, Galway, Ireland*

[4]*Marine Renewable Energy Ireland (MaREI) centre, Galway, Ireland*

About 40% of the world's energy consumption and approximately a third of greenhouse gas emissions are associated with buildings. As the percentage of new buildings relative to existing buildings is increasing at a rate of only 1% per year, retrofitting is recognised as the most immediate, pressing and cost effective mechanism to reduce energy consumption and carbon emissions in the building and construction sector. Preliminary pre-retrofit results of eight case study buildings examining the energy consumption, thermal comfort and human behaviour in typical Irish residential houses built over the last two decades are presented with the impact of human behaviour on energy consumption highlighted. The paper discusses how architects and engineers are going to have to not only understand the complexities of a buildings physics but also the behaviour and attitudes towards energy consumption of the people living inside them in order to develop a holistic retrofit design.

1 INTRODUCTION

The residential building stock of Ireland is among the poorest in terms of energy efficiency in Europe (BPIE 2011). The residential sector accounts for 27% of the country's energy use, emits 10.5 million tonnes of CO_2 annually and is expected to contribute 35% of the energy savings required by the EU (DCENR 2014). The poor energy performance of the building sector is not limited to Ireland alone. The overall building sector of Europe performs poorly in terms of energy efficiency (BPIE 2011).

The Energy Performance Building Directive (EPBD) has introduced directives since its inception in 2002 targeting widespread reduction in building operational energy consumption and carbon emissions in EU member states (European Commission 2002; European Commission 2010a). A significant objective of its latest directive (EPBD 2010/31/EU (recast) (European Commission 2010a)) is the mandatory introduction in all member states of nearly zero energy buildings (NZEB) for all new buildings or those receiving significant retrofit from 2020 (from 2018 for public buildings). A NZEB is a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including those produced on-site or nearby. This legislation will help EU member states achieve their short and long term energy and carbon reduction goals (Commission of European Communities 2007; European Commission 2011).

The European building stock is increasing at a rate of only 1% per year (BPIE 2011). Therefore, retrofitting the existing housing stock is recognised as the most immediate, pressing and cost effective mechanism to reduce energy consumption and carbon emissions in the building and construction sector (E2APT 2010). The current retrofitting rate of households is 1.2%-1.4% per annum (European Commission 2010b). In order to reach the EU short and long term goals for energy and carbon reductions, it is required to double or triple this rate (European Commission 2010b).

2 IRELAND'S BUILDING STOCK

The total number of dwellings in Ireland in the most recent 2011 Census was 1,994,845 (CSO 2012). The Irish housing stock has been ranked the youngest of all of the EU Member States (DCENR 2014). However, over a third of the Irish dwellings were built before 1980 (Figure 1). Of the occupied households (1,649,408), detached houses are the most common type of dwelling in Ireland (42%). These are primarily located in rural areas (72%), are larger than the average European house and primarily use solid fuels or oil based heating systems.

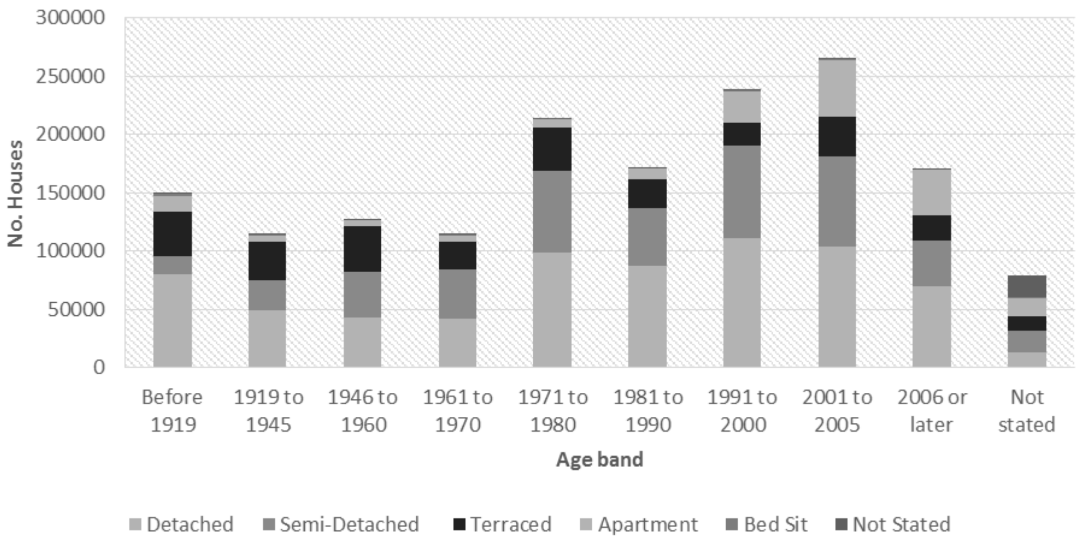

Figure 1 Age bands of the Irish residential building stock (CSO 2012)

The Building Energy Rating (BER) assessment system was set up due to the requirements of EPBD 2002 (European Commission 2002). BERs are calculated by a standard assessment procedure, which models the building's operational energy consumption and carbon emissions using building technical details, standard occupancy and normal climatic conditions, in line with European legislation (EP and CEC 2002). A BER rates the energy performance of buildings on a simple scale of A1 to G.

In total 577,622 BER's have been completed on Ireland's residential building stock (SEAI 2015). The most common BER rating of Irish residential houses is a D1 for which the minimum primary energy usage requirement is 225 kWh/m^2/year. A cost optimum analysis conducted by the Department of the Environment, Heritage and Local Government in Ireland (DECLG 2012) suggested that revised building regulations in Ireland would set the maximum primary energy usage requirement of new NZEB buildings at 45 kWh/m^2/year. This equates to a BER certificate of A2. For retrofit NZEB's, it is estimated the maximum primary energy usage requirement will be 150 kWh/m^2/year. This equates to a BER rating of C1 or better. With 76% of the currently rated buildings having a rating of C2 or worse, a significant amount of work is required in order to get the building stock to the required standard.

There are limitations associated with the BER assessment. A BER accounts for the energy required for lighting, heating and ventilation purposes. However, a BER does not account for the impact of human behaviour in its assessment procedure. It assumes standard occupancy and normal climatic conditions and does not account for the energy required by building appliances (e.g. kitchen appliances, laundry equipment, TVs, etc.). It is estimated that possibly as much as 30% of household primary energy consumption is not included in the BER assessment (Curtis & Pentecost 2014).

However, there is a limitation with the energy savings associated with upgrading building technologies. Energy efficiency is a complex issue spanning different disciplines including engineering, architecture and the social sciences. Existing social research demonstrates that there is significant potential for energy savings through behavioural change initiatives that complement technical interventions (EEA 2013). Thus, it is necessary to investigate people's energy-related habits and attitudes, possibilities for changing them and the energy savings that could be made through these changes. This paper presents preliminary pre-retrofit results of eight case study buildings examining the energy consumption, thermal comfort and human behaviour in typical Irish residential houses built over the last two decades with the impact of human behaviour on energy consumption highlighted. The paper discusses how architects and engineers are going to have to not only understand the complexities of a buildings physics, but also the behaviour and attitudes towards energy consumption of the people living inside them in order to develop a holistic retrofit design.

3 METHODOLOGY

A study involving retrofitted social housing in Dublin, Ireland is currently on-going with 23 houses involved. Surveys were carried out in February/March 2015 prior to energy retrofitting works with the residents of the houses. Information was gathered with respect to the demographic profiles of the tenants, their attitudes towards energy consumption and conservation, quality of life and the environment, what items they consider to be necessities or luxuries in their lives, their everyday energy practices and their thermal satisfaction within their homes.

The survey used in this study built on an existing lifestyle survey developed by social scientist researchers as part of the CONSENSUS Project (Lavelle & Fahy 2012). CONSENSUS (Consumption, Environment and Sustainability) was a seven-year collaboration (2009-2015) between the National University of Ireland, Galway and Trinity College Dublin that investigated behaviours and attitudes in four key areas of household consumption (transport, energy, water and food). The CONSENSUS Lifestyle Survey, a key element of CONSENSUS, involved the collection and analysis of data from 1,500 households in Counties Derry/Londonderry, Dublin and Galway. To ensure maximum comparability with CONSENSUS data, questions from the CONSENSUS Lifestyle Survey were used again. Regarding data collection, face-to-face surveys were conducted with an adult aged 18 years or older prior to the installation of data logging instrumentation in each of the houses.

The temperature, relative humidity and electricity usage profiles of the 23 houses in Dublin are being monitored using data logging instrumentation. The temperature and relative humidity profiles of 23 houses are currently being monitored at high resolution (i.e. 15 minute interval readings). Electricity usage profiles are currently being monitored at 60 minute intervals within 20 of the houses. Electricity and gas meter readings are being recorded once a month for each of the houses in the estate. Residents are asked to record if they purchase solid fuel as they have the option of using solid fuel as a secondary heating source in the living rooms.

4 RETROFIT CASE STUDY

The social housing estate in Dublin involved in the study is located in a suburb area of Dublin, Ireland. The estate was constructed in two phases. The first phase in 1994 which consisted of 32 end- and mid-terraced houses and 14 apartments. The mid and end terrace houses constructed in 1994 are shown in Figure 2(a). The end- and mid-terraced houses are two-storey buildings with a total of six rooms in each of the buildings. These six rooms are divided into three bedrooms and individual kitchen, living and bathroom spaces. The apartments are not involved in the study.

An additional 30 residences – 24 end- and mid-terraced houses and 6 semi-detached houses were constructed in 2000. The mid and end terrace houses constructed in 1994 are shown in Figure 2(b). Each building has two storeys with a total of seven rooms: three bedrooms, two bathrooms and individual kitchen and living spaces. Home heating systems in the residences comprise of a gas-fired boiler as a central heating system with either a solid fuel open fire, gas fire or electric fire acting as a secondary heating system in the living room. 23 of the 76 households in the estate agreed to participate in the study.

Figure 2(a) Mid- and end-terraced houses constructed in 1994 and Figure 2(b) Mid- and end-terraced houses constructed in 2000

4.1 *Scope, scale and nature of retrofitting programme*

Upgrade retrofit works were completed at the end of October 2015 in the 23 homes in Dublin. Table 1 details the construction year, house type and building element characteristics pre and post retrofit of the houses involved in study (see Table 2 for the characteristics of each of the building elements before and after they were retrofitted referenced in Table 1).

In the houses constructed in 1994, attic insulation was installed along with new PVC windows, front door and back patio doors and condensing gas boiler. A thermostat controlling the temperature of the hallway and heating schedules of the gas boiler was also installed. Only a section of the 1994 houses received cavity insulation as the buildings were mainly solid walls constructed using concrete masonry cavity blocks with interior dry-lining using gypsum board. A section of the exterior wall on the ground floor adjacent to the living room was constructed with cavity wall construction. This cavity was pumped with bead insulation.

The houses constructed in 2000 received the same attic insulation, windows, front door, back patio doors, gas boiler and thermostat upgrades as the 1994 houses. However, the exterior walls of these houses were built using cavity wall construction. Therefore, all of the exterior walls of these houses were pumped with cavity insulation.

Table 1. Details of the construction year, house type and building element characteristics pre and post retrofit involved in study. Refer to Table 2 for the characteristics of the building elements referenced in Table 1

Construction Year	House Type	Total Houses	External Walls		Attic		Windows		Doors		Main Space and Water Heating System	
			Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
1994	Mid-Terrace	4	1, 2	1, 3	6	7	8	10	11	13	14	16
1994	End-Terrace	7	1, 2	1, 3	6	7	8	10	11	13	14	16
2000	Mid-Terrace	4	4	5	6	7	9	10	12	13	15	16
2000	End-Terrace	5	4	5	6	7	9	10	12	13	15	16
2000	Semi-Detached	3	4	5	6	7	9	10	12	13	15	16

Table 2. Characteristics of the building elements pre and post retrofit

Reference Number	Building Element
	External Walls
1	Concrete masonry cavity blocks with interior dry-lining using gypsum board.
2	A section of the exterior wall on the ground floor adjacent to the living room was cavity wall construction with clay fired brick exterior leaf, 50mm cavity rigid board insulation (U-value=0.035 W/mK), 50-150mm residual cavity air gap and concrete masonry block interior leaf
3	A section of the exterior wall on the ground floor adjacent to the living room was cavity wall construction with clay fired brick exterior leaf, 50mm cavity rigid board insulation (U-value=0.035 W/mK), Cavity pumped with 50-150mm bonded bead insulation (U-value= 0.035 W/mK)
4	Cavity wall with concrete masonry block internal and external leaf, 60mm cavity rigid board insulation (U-value=0.035 W/mK) with 60mm residual cavity air gap
5	Cavity wall with concrete masonry block internal and external leaf, 60mm cavity rigid board insulation (U-value=0.035 W/mK) with 60mm pumped cavity bonded bead insulation (U-value= 0.035 W/mK).
	Attic Insulation
6	Standard timber gable-end roof, rafters with ceiling insulation 100mm fibreglass (U-value=0.044W/mK) in between ceiling joists
7	Standard timber gable-end roof, rafters with ceiling insulation 100mm fibreglass (U-value=0.044W/mK) in between ceiling joists and 300mm glass mineral wool U-value= 0.044 W/mK) on top of ceiling joists
	Windows
8	12mm double glazed argon filled PVC framed windows (U-value= 3.1 W/m^{2}K)
9	12mm double glazed argon filled timber framed windows (U-value= 3.1 W/m^{2}K)
10	24mm double glazed argon filled PVC framed windows (U-value= 1.5 W/m^{2}K)
	Doors
11	Timber framed front door and uPVC patio doors (U-value= 1.8 W/m^{2}K)
12	uPVC framed front door and patio doors (U-value= 3 W/m^{2}K)
13	uPVC framed front door and patio doors (U-value= 3 W/m^{2}K)
	Main Space and Water Heating System
14	Gas Boiler (79% efficient)
15	Gas Boiler (77% efficient)
16	Gas Boiler (94% efficient) and thermostat temperature control

4.2 *Quality of housing*

Regarding the construction quality of housing in Dublin, some significant problems emerged during initial exploration on site. Mould or dampness was recorded in 20 of the 23 Dublin homes (86.9%). There were common complaints of mould in the corners of bedrooms in all houses, particularly in the box room located at the front of the house over the entrance hallway. Furthermore, mould was reported along the skirting boards of houses. Figure 3 highlights the thermal bridging along the skirting boards in a house constructed in 2000

A majority of the homes complained of excess drafts entering via badly sealed openings (windows and doors) at the front of the house with a less significant impact at the back of the houses. Some houses highlighted their warped doors allowing drafts to enter the houses. Figure 4 highlights the thermal bridging experienced at the front door of a house constructed in 1994. A majority of the houses complained of condensation on the windows with the bedroom windows the main focus of the complaints. Several tenants noted that the central heating is required to be constantly on as once it is turned off all the heat escapes and the houses are immediately cold once again. The box room at the front of the house came in for particular criticism from the householders with many stating it to be the coldest room in the house due to excessive drafts.

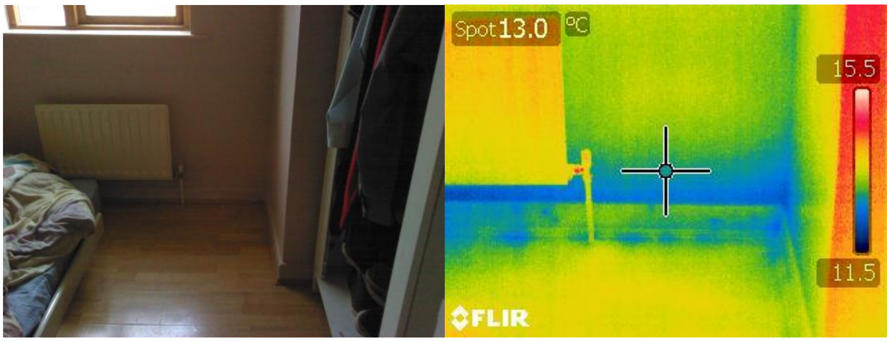

Figure 3. The thermal bridging along the skirting boards of a house constructed in 2000

Figure 4. The thermal bridging experienced at the front door of a house constructed in 1994

5 RESULTS

Preliminary pre-retrofit results of the survey data, internal temperature profiles and electricity and gas meter readings of eight of the houses involved in the study are shown in Table 3. The table shows two different versions of the end and mid terraced houses constructed in 1994 and 2000 to highlight the impact the people living inside them has on their energy usage and internal temperature profiles

The total number of people in the houses range from one to four. The thermal comfort results of the surveys highlight the poor condition the houses were in previous to the refurbishment works. Six of the eight houses were dissatisfied or worse with the thermal comfort of their homes. The two houses who were satisfied had the highest average daily gas usage of the houses. Seven of the eight homes considered their homes to be too cold or worse in both the morning and evening time in the winter. The residents were asked on an average weekday and weekend the number of hours in the day that there is somebody present in the home. In all but two of the houses there was typically someone present in the home throughout the day.

The average internal temperature profiles for the month of March 2015 experienced in the living room and kitchen of the eight households are given. Comparing the two versions of each of the same house types given, the impact the people inside them has on the internal temperature profile is evident. The two end terraced houses constructed in 1994 have an average temperature difference of 2.2°C and 3°C in the living room and kitchen. The householders with the higher average temperate are reported to be satisfied with the warmth of their house whereas the one with the lower average temperatures are reported to be very dissatisfied. Similar results are shown for the end terraced houses constructed in 2000 except with a larger temperature differential. The house reported to be satisfied with the warmth of their house have average temperatures of 20.1°C in their living room and kitchen for the month of March. The household who are very dissatisfied with the warmth of their homes have average temperatures of 15.8°C and 15.4°C in their living room and kitchen.

The high average temperature profiles of the houses are reflected in their average daily gas usages. The average daily pre-retrofit electricity and gas usage given below in Table 3 accounts for 160 days (12^{th} February 2015 to 22^{nd} July 2015). None of houses reported the usage of solid fuel to heat their homes. All of the houses mainly relied on their gas boiler for their central and water heating according to the survey.

Table 3. Preliminary results of the survey data, electricity and gas meter readings of eight of the houses involved in the study

Case Study	1	2	3	4	5	6	7	8
House Details								
House Type	End Terrace	End Terrace	Mid Terrace	Mid Terrace	End Terrace	End Terrace	Mid Terrace	Mid Terrace
Construction Year	1994	1994	1994	1994	2000	2000	2000	2000
Occupancy								
No. of years lived in house?	10 or more	10 or more	0-1 year	10 or more	10 or more	10 or more	2-5 years	10 or more
House Composition								
Total No. People	1	2	4	3	4	2	4	3
Adults (>18 Years)	1	2	1	3	2	1	1	3
Teenagers (15-18 Years)	0	0	0	0	2	0	0	0
Children (<=14 years)	0	0	3	0	0	1	3	0
Average No. of Hours Someone is Present in House on a:								
Weekday	19	24	24	24	24	24	19	24
Weekend	24	24	24	24	24	24	24	24
Rate the Warmth of the House								
	Very dissat-isfied	Satis-fied	Very dissat-isfied	Dissat-isfied	Satis-fied	Very dissat-isfied	Dissat-isfied	Dissat-isfied
Rate the Internal Temperature and Level of Comfort in the Winter in the:								
Morning	Much too cold	Com-fortable	Much too cold	Much too cold	Much too cold	Much too cold	Much too cold	Much too cold
Winter	Too cool	Com-fortable	Much too cold	Much too cold	Much too cold	Much too cold	Much too cold	Much too cold
Average Temperature March 2015 (°C)								
Living Room	18.2	20.4	19.4	20.1	20.1	15.8	18.7	19.4
Kitchen	17.8	21.8	19.3	21.7	20.1	15.4	17.6	18.1
Average Daily kWh Energy Usage:								
Electricity	7.2 (7.2)	7.1 (7.9)	11.0 (8.5)	15.7 (15.0)	17.1 (16.8)	9.3 (10.5)	9.0 (9.1)	10.0 (10.1)
Gas	21.9 (37.8)	29.1 (52.6)	15.3 (31.0)	25.8 (50.0)	33.5 (53.1)	11.1 (15.2)	18.1 (32.0)	16.9 (34.4)

Highlighted in brackets are the average daily electricity and gas usages of the houses for the month of March for comparison with their respective temperature profiles. For both the mid terraced houses constructed in 1994, there is reported to be someone present in the house 24 hours a day on both an average weekday and weekend. However, based on both households' average room temperatures and average daily gas usages for March, both set of residents have different heating strategies in their homes. Their heating strategies can be influenced by a number of factors including what they perceive to be a comfortable temperature in their household, how often they ventilate their houses, the type of clothes they wear in their house and the level of income available to them to spend on their heating. From the data collected in the surveys with a member of the households, the house with the lowest temperature and gas usage has the lowest annual income of all the 23 houses involved in the study.

The type of house will have an impact on the building's heating requirements. Of the four different housing type and construction year variations, the largest gas usage difference can be seen in the end terraced houses constructed in 2000. The smaller consumer (case study 6) uses 33% of the larger consumer (case study 5).

Each of the households rely on gas for their central and water heating purposes. Therefore their average electricity use would not be significantly dependant on the type of household but rather on their appliance and lighting usage. The smallest daily average electricity consumer (case study 2) consumed 41.5% of the highest daily consumer (case study 5) despite both houses reporting someone to be present in their houses 24 hours on an average weekday and weekend.

6 DISCUSSION AND CONCLUSIONS

There was a lack of communication between the residents, property management company, contractors and architects in the planning phase which led to problems during the refurbishment works phase. Residents of the houses constructed in 1994 were told their houses would be insulated with pumped cavity insulation, as it was assumed these houses were constructed with cavity walls. During the works, it was discovered that the majority of these houses were instead constructed with hollow block walls. Therefore, these walls were unable to be pumped with insulation. A section of the exterior wall on the ground floor adjacent to the living room was constructed with cavity wall construction. This cavity was pumped with insulation.

No options were given to residents in regards to the type of technologies that would be installed in their houses during the works. Each of the houses got a new front door and back patio doors. Initially, the front doors installed had large transparent glass panels. The residents of the houses complained that there was a lack of privacy with these doors and wanted them to be changed. In order to combat this, the large glass panels were frosted which increased the cost of their production. Due to this extra cost, the back patio door were changed. Initially, the back patio doors had two opening doors but this was reduced to one due to the increase cost of the front door.

Presently, improving the energy efficiency in existing residential buildings is most often addressed by a 'standard' retrofit. This is the upgrading of inefficient building systems, such as lighting, hot water tank insulation, windows, doors, etc. with better-performing building technologies. This 'standard retrofit' reduces the energy requirements of existing buildings. There is a limitation with the energy savings associated with upgrading building technologies. Existing social research demonstrates that there is significant potential for energy savings through behavioural change initiatives that complement technical interventions (EEA 2013). The impact of human behaviour on residential energy consumption has been highlighted in the results given in this paper (Table 3) and in other studies (Gill et al. 2010; Gram-Hanssen 2010). Thus, it is necessary to investigate people's energy-related habits and attitudes, possibilities for changing them and the energy savings that could be made through these changes.

Thus, architects and engineers are going to have to not only understand the complexities of a buildings physics but also the behaviour and attitudes towards energy consumption of the people living inside them. They are going to have to treat each building as a completely different system as the retrofit design of one building may not suit the needs of another due to the impact of human behaviour. There needs to be strong and experienced project leader to co-ordinate the project in an efficient manner and include all major stakeholders from an early part of a project. This is required in order to adopt a holistic approach to a retrofit design which can produce significantly larger energy savings.

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