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# Changing energy cultures? Household energy use before and after a building energy efficiency retrofit

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ABSTRACT

Government- and community-initiated energy retrofits of existing residential buildings abound across Europe. This paper argues that retrofitting initiatives need to extend their current emphasis on technical-material changes to include an equally strong focus on researching and potentially changing the energy-related expectations, aspirations and actual activities of those who inhabit and use these buildings. The concept of energy cultures serves as a useful heuristic to structure the analysis of household energy demand and internal environment. Covering three key elements of energy culture – 1) material conditions that relate directly to domestic energy use, 2) householders' attitudes, perceptions and norms concerning the use of energy and 3) observable everyday practices that use energy –, and their interactions, we examine data from 20 households in a social housing estate in Ireland collected before and after retrofitting. Overall, the results highlight the urgent need for an integrated approach to energy retrofitting that combines technology-aided changes in material conditions with a parallel re-shaping of householders' views and practices to achieve real and lasting reductions in energy use. The latter seems particularly pressing given both the persistence of many energy-intensive domestic activities and the possible emergence of rebound effects that have the potential to cancel out at least some of the savings made through retrofitting.

## 1. Introduction

Governments across Europe have directed considerable attention and resources towards retrofitting programmes aimed at improving the energy efficiency of residential buildings through technical means. In Ireland for example from 2000 to 2016, 375,000 Irish homes received government grants to retrofit their homes to a higher energy efficiency standard (SEAI, 2018b) through multiple grant schemes (DCENR, 2013). While useful in many respects, limitations exist with regard to the savings that can be achieved by upgrading buildings, with studies reporting average energy saving deficits to range from 14 % to 98 % (Calì, Osterhage, Streblow, & Müller, 2016; Energy Consulting Network & Tipperary Energy Agency, 2013; Energy Savings Trust to Ofgem, 2003; Fowlie, Greenstone, & Wolfram, 2015; Gupta & Gregg, 2016; Henderson, Staniaszek, Anderson, & Phillipson, 2003; Hens, 2010; Hens, Parijs, & Deurinck, 2010; Hong, Oreszczyn, & Ridley, 2006; Majcen, Itard, & Visscher, 2016; Scheer, Clancy, & Hógáin, 2013). Scheer et al. (2013) found a shortfall in energy savings ranging from 28 to 44 % for homes involved in the Better Energy Homes scheme which provides grants to Irish homeowners for energy efficiency retrofits.

Limitations in energy savings can relate to observable short-term and long-term variations in household energy use that are attributable to the dynamics of everyday life (Gill, Tierney, Pegg, & Allan, 2010; Gram-Hanssen, 2010). These complement (and perhaps even supersede in importance) 'classical' socio-economic factors such as household size and composition (Druckman & Jackson, 2008; McLoughlin, Duffy, & Conlon, 2012; Wyatt, 2013; Yohanis, Mondol, Wright, & Norton, 2008), household income (Druckman & Jackson, 2008; McLoughlin et al., 2012; Sanquist, Orr, Shui, & Bittner, 2012; Schaffrin & Reibling, 2015; Wyatt, 2013), and tenure type (Belaid, 2016; Druckman & Jackson, 2008; Wyatt, 2013; Yohanis et al., 2008).

For example, a post-occupancy evaluation of the actual energy performance of 11 new low-energy dwellings in the UK revealed that 51 %, 37 % and 11 % of the variance in heat, electricity and water

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consumption, respectively, between dwellings related to variations in householders' everyday activities and habits (Gill et al., 2010). Similarly, a systematic comparison of heating-related energy demand of five identical residential buildings in Denmark showed large variances arising from differences in how occupants used these buildings (Gram-Hanssen, 2010). Evidence also exists of post-retrofit increases in energy use which (partly) cancelled out gains made through retrofitting (Druckman, Chitnis, Sorrell, & Jackson, 2011). These so-called rebound and 'backfire' effects can vary in both manner and scale (Chitnis, Sorrell, Druckman, Firth, & Jackson, 2014; Hertwich, 2005), which suggested that post-retrofit changes in occupants' habits and related aspects of energy use deserved much greater attention than has hitherto been the case.

This study of pre- and post-retrofit energy use builds on existing research, linking conceptual groundwork with a detailed multi-method empirical investigation of 20 Irish households that have undergone an energy retrofit. Section Two outlines the conceptual framework, drawing on previous work on energy cultures. This is followed by details regarding data collection and analysis (Section Three). Section Four presents empirical data that reflect the three main elements of energy cultures: (i) material conditions, (ii) attitudes, perceptions and social norms concerning energy use, and (iii) actual practices that all incur some form of energy use. Selected household characteristics that influence how these three elements manifest themselves within individual households are also considered. Finally, the benefits and drawbacks of using an energy-cultural approach to investigation variations in energy use both across households and before and after the retrofit are discussed (Section Five).

## 2. The use of social science in understanding domestic energy use

A lack of social dimensions in energy research (Sovacool et al., 2015; Vilches, Garcia-Martinez, & Sanchez-Montañes, 2017) has led to calls for social-scientific energy research capable of addressing the gap that between the expected and actual energy use of building occupants installing energy efficiency retrofit measures (Pombo, Allacker, Rivela, & Neila, 2016; Touceda, Neila, & Degrez, 2018). In this context, social-scientific research on the cultural dimensions of domestic energy use has gained momentum of late (2010, Stephenson et al., 2015a; Stephenson, 2018), following some initial pioneering work (Lutzenhiser, 1992; Wilk & Wilhite, 1985; Wilk, 2002). In fact, a considerable number of social-scientific and interdisciplinary energy studies have deployed the concept of energy cultures to integrate social, cultural and material factors into the analysis of domestic energy use and its transformation (Lutzenhiser, 1992; Pfister & Schweighofer, 2018; Stephenson et al., 2010, 2015a; Wilhite, Shove, Lutzenhiser, & Kempton, 2000; Wilk, 2002). While these vary in terms of focus and priorities (e.g. individual behaviour versus collectively shared practices; personal attitudes versus socially negotiated norms), they all move beyond existing technocentric work that views energy use as largely determined by physical and material conditions and that ignores the central role of people's habits and routines in shaping energy demand in the home. This growing body of work includes anthropological, sociological and interdisciplinary inquiries into activities that are inextricably linked to household energy use (e.g. eating and cooking, mobility).

### 2.1. Conceptual framework: energy cultures

The concept of energy cultures has emerged as a framework or heuristic for investigating domestic energy use across different scales and social groupings (Barton et al., 2013; Stephenson et al., 2015a, 2010). It combines an emphasis on social and cultural norms and actual energy use with a focus on prevailing material conditions, fusing elements from a range of culture-sensitive approaches to the study of energy use. This paper draws explicitly on the Energy Cultures framework (ECF) developed by Stephenson et al. (2010, 2015a) because of its proven track record as an integrative conceptual foundation for multi-, inter- and transdisciplinary energy research. The ECF treats energy use as collectively shared and culturally mediated, while also recognising its contingency upon factors relating to both material systems and individuals' characteristics and activities (e.g. behaviour intentions guided by internalised norms). Originally developed for multidisciplinary research on energy behaviour (Stephenson et al., 2015a), including reasons for the (in)effectiveness of state-led efforts to increase consumer energy efficiency, the ECF has also proved its worth in inquiries into the dynamics of energy use at different scales (e.g. local, regional, national and international).[1]

The field of energy cultures research displays significant theoretical and conceptual divergences. For example, vast variations exist in how the role of individuals and their capacity to bring about change are viewed and portrayed. Here, approaches that prioritise individuals' behaviour contrast (and sometimes clash) with practice-oriented views that treat individuals largely as 'practitioners' or 'carriers of practices' (Shove & Pantzar, 2007); refer to (Pfister & Schweighofer, 2018) for a discussion of these tensions. On the practice-theoretical side, many authors have criticised the persistent dominance of approaches that overemphasise the role of the individual in energy consumption. For example, Shove and Walker (2010) calls for a move 'beyond the ABC'; that is, the dominant model of human behaviour that assumes a linear connection between attitude (A), behaviour (B) and choice (C). Similarly, Spurling, Mcmeekin, Shove, Southerton, and Welch (2013) argue that 'social practices are a better target of intervention for sustainability policy than 'behaviour', 'choice' or technical innovation alone'.

In contrast, ECF advocates have been less concerned with a shift in attention away from individual behaviour. Instead, they have developed 'a structure for addressing the problem of multiple interpretations of 'behaviour' by suggesting that it is influenced by the interactions between cognitive norms, energy practices and material culture' (Stephenson et al., 2010). This difference in focus on individuals and practices, respectively, is perhaps the most significant source of tension within the energy cultures debate (see Greene & Rau, 2018; Shove & Walker, 2010; Spurling et al., 2013; Stephenson, 2018). This said, this tension remains largely unresolved, with different approaches co-existing.

Different variants of energy cultures thinking also diverge in their view of how practices become entrenched and hard to change and what causes this inherent 'stickiness' (Hansen, 2018). Some ascribe the longevity of particular practices to individuals' hard-to-shift habits and routines but emphasise possibilities for transformation through behaviour change. For example, responding to the observable persistence of daily routines and habits and related patterns of energy use in the face of change initiatives, Stephenson et al. (2010) presented the ECF as a tool to assist in understanding the factors that influence energy consumption behaviour, and to help identify opportunities for behaviour change. In contrast, many practice-theoretical approaches recognise the significance of entrenched structures, including prevailing systems of provision and established (sets of interlocking) practices (Spurling et al., 2013) in shaping actual and potential change trajectories.

Overall, these divergent, yet complementary strands of thinking about energy cultures, that is, particular combinations of individuals' (routine) actions and the socio-technical settings within which these occur, have produced important social-scientific insights into the nature and dynamics of domestic energy use, albeit with different foci. The decision to use the ECF to conceptually frame the empirical material

[1] For example, the EU-H2020-funded ENERGISE project, a multidisciplinary effort to understand and potentially transform domestic energy use, uses an innovative conceptual framework that fuses energy cultures thinking with insights from practice theory and that introduces the linking concept of 'practice cultures' (Greene & Rau, 2018).

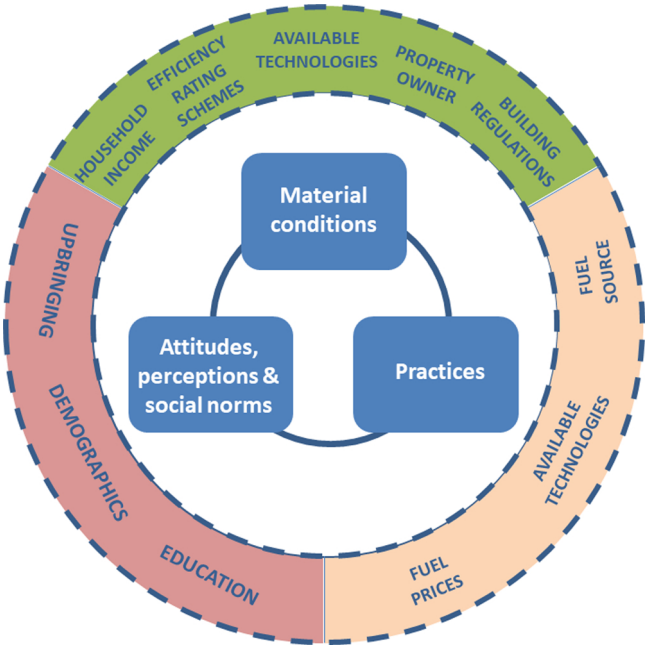


**Fig. 1.** Energy culture: Key elements and systemic influences. (adapted from Stephenson et al. (2010)).

presented in this paper was primarily informed by epistemological and methodological considerations. Given the history of the ECF as a heuristic for structuring multidisciplinary, multi-method research on energy use, it was deemed to be particularly suitable for the research presented herein. Moreover, it was evident from the beginning of the project that it would need to speak to the behaviour change agenda in energy policy both in Ireland and internationally, and also connect with the associated scientific and 'grey' literature.

### 2.2. Using the ECF to investigate energy retrofitting programmes

As outlined above, this study draws directly on the ECF developed by Stephenson et al. (2010, 2015a, 2015b) and further elaborated by Stephenson (2018). It distinguishes between three key elements that contribute to the formation of distinct energy cultures: 1) prevailing material conditions (e.g. technologies, energy infrastructure), 2) attitudes, perceptions and socially shared norms regarding energy use (e.g. whether wasting energy is seen as acceptable in society, expectations regarding thermal comfort), and 3) actual practices that make up everyday life such as heating and cooling, cooking, or washing, and that all involve the (direct or indirect) use of energy (see inner circle in Fig. 1).

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

Energy cultures interact with contextual factors and influences (Fig. 1). As Stephenson et al. (2010) emphasise, 'wider influences are not exogenous to the energy culture, but exert influence and are in turn influenced by it — for example, law and policy are affected by values, aspirations, beliefs and understandings, and in turn affect them' (p. 6124). The dashed circle in Fig. 1 suggests a high level of permeability between the three energy culture elements and the wider context. Importantly, these systemic influences might pertain to dynamic social phenomena such as energy policy and regulation (e.g. efficiency rating schemes, building regulations) or demographic conditions (e.g. the rise in the number of single households).

The ECF has been used to understand how cultural formations result in sustainable outcomes that are of interest (Stephenson, 2018). The ECF has been applied to a number of studies revolving around residential buildings including understanding the challenges of living in fuel poverty (McKague, Lawson, Scott, & Wooliscroft, 2016), the energy cultures of the elderly which are driving energy consumption (Bardazzi & Pazienza, 2017) and comparing the impact of home audits and community events resulting in a change in householders energy cultures (Scott, McCarthy, Ford, Stephenson, & Gorrie, 2016).

In Stephenson's examination of how the ECF has been applied in research to date (Stephenson, 2018), the author provides areas of exploration of where the ECF can be used. One area includes examining how aspects of an actors' culture and the sustainability-related outcomes are affected if one aspect of the actors' culture changes. Another area includes examining how changing or unchanging sustainability outcomes are due to aspects of an actors' culture. In this paper, both of these areas are explored using qualitative and quantitative data collected from 20 Irish households that have undergone a material focused energy efficiency retrofit. A careful operationalisation of the three constitutive elements of energy culture (Table 1) made it possible to empirically investigate a) the impact energy efficiency retrofitting has on the energy cultures and the sustainable-related outcomes among inhabitants of urban co-operative social housing units in Ireland and b) examine possible relationships between energy efficiency retrofitting, domestic energy use practices, material conditions and the attitudes, perceptions and social norms of householders with regards to the energy related outcomes. In this paper, building energy use and the internal environment are indicators employed as examples of sustainable-related outcomes. The following section details the methodology used, including the careful operationalisation of the ECF for data collection and analysis.

## 3. Methodology

### 3.1. Data collection

To understand how a particular change in material conditions affects householders' attitudes, perceptions and social norms as well as

**Table 1**
Operationalisation of the three elements of the Energy Culture Franework (ECF).
Source: Authors' extension of Stephenson et al. (2010, 2015b).

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

their practices and energy-related outcomes, this analysis draws on detailed data from 20 households whose homes underwent an energy efficiency retrofit in autumn 2015. The paper makes use of both qualitative and quantitative data collected from the households pre- and post-retrofit. To apply the ECF to the analysis of the retrofit, it was necessary to gather data across the three ECF elements and the energy-related outcomes using: (i) pre-retrofit and post-retrofit participant surveys, (ii) installation of data-logging instrumentation, and (iii) monthly readings of electricity and gas meters.

To gather information on the household characteristics and energy cultures of the householders, prior to the retrofitting works carried out, surveys on the physical characteristics of the buildings were conducted and face-to-face semi-structured surveys were conducted with an adult (aged 18 years or older) in each household. Information was gathered on the demographic profiles of all householders, their attitudes towards energy use and conservation, quality of life and the environment, which items they viewed to be necessities or luxuries, their energy-related practices, and their thermal satisfaction within their homes. One year later, participants completed a similar post-retrofit survey, designed to examine changes in each household's material conditions, attitudes, practices and characteristics. Open-ended questions regarding the householder's attitudes towards the material changes to their house from the energy efficiency retrofit and how it affected their energy consumption were included in the survey. Both surveys used in this study built on an existing lifestyle survey deployed as part of the Consumption, Environment and Sustainability (CONSENSUS) project, an EPA-Ireland funded 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 (Davies, Fahy, & Rau, 2014; Lavelle & Fahy, 2012).

Building energy use and the internal environment were the sustainable-related outcomes of focus in this study. Gas is used to operate the gas boiler which is the primary heating system in the houses for providing space heating and domestic hot water heating. Electricity is also used to operate the secondary domestic hot water heating system (electric immersion in hot water tank).

The pre-retrofit and post-retrofit heating season gas usages are normalised using Heating Degree Days (HDDs) based on the external temperatures experienced at Dublin airport from February to May during 2015 and 2016 (Met Éireann, 2016). A base temperature of 15.5 °C is assumed in this analysis.[2] The normalised gas usage data (kWh/HDDs) for each phase is multiplied by the average HDDs experienced at Dublin Airport from February to May for 10 years starting from 2005.

Data-logging instrumentation was installed in each of the houses to record characteristics of the indoor environment. Temperature and relative humidity data loggers were placed in multiple rooms. These data loggers were unobtrusive and recorded data at one-hour intervals pre-retrofit and 15-minute intervals post retrofit. Finally, electricity and gas meter readings were recorded once a month for each of the houses. The figures for gas and electricity use presented in this paper correspond to secondary energy and do not account for losses across the network. Six months of pre-retrofit energy use data (12th February - 22nd July 2015) and six months of post-retrofit energy use data (13th February - 21st July 2016) have been analysed.

### 3.2. Data analysis

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

For the material conditions element, the physical characteristics of the building, including terrace position, orientation, external walls, attic insulation, windows, and heating systems were considered, in addition to the number of appliances owned by the tenants (see Table 3).

Five indicators were selected for the attitudes, perceptions and social norms element (Table 3): perceived comfort levels (thermal comfort), perceptions of appliances as necessities or luxuries, desired benefits of the retrofit, preferences concerning incentives and environmental attitudes. A list of ten pro-environmental attitude statements that mirrored those in the CONSENSUS Lifestyle Survey (Lavelle & Fahy, 2012) were used, as listed in Table 2 .

Households could score between 10 and 50 points, with a higher score indicating a stronger pro-environmental attitude. Furthermore, three appliances were chosen for comparison across all households: dishwasher, TV and games console. These appliances were selected because of their availability and because many householders viewed them as a necessity, which made continued ownership and use more likely when compared to other appliances.

Nine indicators represent the practices element of the ECF. It was necessary to summarise some of the indicators using categorical frequencies rather than more detailed information. Information about how (often) the householders operated their space heating and hot water systems is presented using qualitative indicators. To examine the energy cultures of householders in relation to energy consumption, the number of hours lighting is typically turned on, the number of appliances owned by the householders and the frequency of usage of four high electricity consuming appliances (dishwasher, washing machine, tumble dryer and electric shower) were considered.

Other indicators of practices, similar to the examples given in Table 1, were collected during the pre-retrofit and post-retrofit surveys, including hours of heating, heating schedule settings, ventilation practices and use of smaller energy consuming appliances. However, these results were only recorded once during both the pre-retrofit and post-retrofit monitoring period, and they may not be fully representative of householders' practices during the two six-month periods considered.

The energy-related outcomes focused on building energy use and the internal environment. The building energy use is represented using the average daily gas and electricity energy consumption derived from the meter readings for the six-month periods before and after the retrofit. The average daily energy consumption is the sum of the average daily gas and electricity energy consumption. For the internal environment, information on the average temperature of the house during the pre-retrofit and post-retrofit heating season periods is given. A two-sample z-test for comparing two means is used for examining whether houses experienced a statistically significant change (95 % confidence level) in average house temperature profiles. The percentage of time the average temperature was under the thermal comfort range as defined in EN15251 (European Commission, 2006) is also presented pre-retrofit and post-retrofit. The temperature data analysed is based on temperature data collected from the kitchen and living room of each of the case studies. In addition, householders were asked whether there was a presence of mould in their home.

## 4. Results

All selected indicators that connect to the three elements of the ECF plus those that capture the energy -related outcomes and household characteristics are outlined in the following three tables. Table 3 provides an index for the two subsequent tables. Table 4 presents the pre-

[2] Typical monthly average temperatures near the case study site range from 10-16ºC in summer and 4-9ºC in winter (Met Éireann, 2016).

**Table 2**
List of environmental attitude statements (Lavelle & Fahy, 2012).

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

retrofit results for all indicators, followed by post-retrofit results in Table 5. Moreover, the colour scheme in Table 5 marks any post-retrofit changes, drawing readers' attention to them. The case study numbers are the numbers applied to the case study houses in (Moran, 2019). The case study results presented in Tables 4 and 5 are presented in order of lowest to highest energy consumption for the five main types of houses within the study, as defined by construction year and terrace position.

### 4.1. Impact of energy efficiency retrofit on ECF elements

Our analysis focused on the relationship between the energy efficiency retrofitting and changes in indicators that connect to the three elements of ECF and household characteristics across 20 case studies.

**Table 3**
Index of indicators for each ECF element.

| Household characteristics | |
|---|---|
| # Occupants | Number of house occupants |
| # Children | Number of children living in house |
| Gender | Gender of house occupants: F (female), M (male) |
| Empl. Status | Employment status of head of household: 1 (employed); 2 (unemployed); 3 (looking after home); 4 (student); 5 (retired); 6 (Other) |
| Hours Occ. | Hours house occupied during typical day |
| HH Income | Household income (including benefits) in €000s |
| **Material conditions** | |
| Constr. Year | Year house constructed |
| Terrace Pos. | House terrace position: Mid (mid-terrace), End (end-terrace), SD (Semi-detached) |
| Orientation | House orientation: East, West, North, South, South-West |
| Ext. Walls | External walls: HB (hollow block wall for majority of house); CW (cavity wall); PC (pumped cavity wall) |
| Attic Insul. | Attic insulation: 100 mm (100 mm fibreglass between joists); 400 mm (100 mm fibreglass between ceiling joists and 300 mm glass mineral wool on top of ceiling joists) |
| Window | W-6 (Wooden frame double-glazed air filled with 6 mm gap); P-6 (PVC frame double-glazed air filled with 6 mm gap); P-16 (PVC framed double-glazed argon filled with 16 mm gap) |
| Boiler Effic. | Gas boiler efficiency: % |
| 2nd Heating | Secondary heating system: OF (Open Fire); ST (Solid Fuel Stove); GF (Gas Fire); EF (Electric Fire) |
| # Appliances | Number of appliances owned of: dishwasher, washing machine, tumble dryer, TV, PC, games console, microwave, cooker, electric shower, power shower |
| Ventilation | Ventilation strategy: A (Passive vents in windows), B (Passive vents in windows and walls); C (Passive vents in windows and walls and mechanical extracts in kitchen and bathroom) |
| Air-Perm. | Air permeability of building based on a fan pressurization method test carried out to I.S. EN 13829:2000 standards: $m^3/(h.\,m^2)$@50 Pa. |
| **Attitudes, perceptions and social norms** | |
| Thermal Comfort | Thermal comfort: VS (very satisfied); S (satisfied); N (neither satisfied nor dissatisfied); D (dissatisfied); VD (very dissatisfied) |
| Nec. v Lux. | Number of indicator appliances (TV, dishwasher, games console) perceived as necessities |
| Benefit | Desired/perceived post-retrofit benefit: 1 (reduce your energy bills); 2 (increase in the comfort level); 3 (improve the environment) |
| Incentives | 1 (financial incentives/grants); 2 (lower utility bills); 3 (information/campaigns); 4 (better labelling); 5 (peer support); 6 (none of the above) |
| Env. Att | List of 10 pro-environmental attitudes statements (Lavelle & Fahy, 2012; see Table 2); five-point scale: strong agreement (5) to strong disagreement (1) |
| **Practices** | |
| CH Freq. | Central heating frequency of usage during winter: 1 (daily); 2 (few times per week); 3 (few times per month); 4 (never) |
| CH Set. | Space heating controller operation settings: P (space heating controlled with schedule and thermostat); P/M (space heating controlled with schedule and thermostat and manually operated by householder); M (space heating manually operated by householder) |
| WH Freq. | Water heating frequency of usage during winter: 1 (daily); 2 (few times per week); 3 (few times per month); 4 (never) |
| WH Sec. | Does householder use electrical immersion for domestic water heating: Yes; No |
| Hrs Lights on | Hours lights on inside house on typical day |
| Dishwasher | Water heating frequency of usage during winter: 1 (daily); 2 (few times per week); 3 (few times per month); 4 (never) |
| W. Machine | Water heating frequency of usage during winter: 1 (daily); 2 (few times per week); 3 (few times per month); 4 (never) |
| Tum. Dryer | Water heating frequency of usage during winter: 1 (daily); 2 (few times per week); 3 (few times per month); 4 (never) |
| Elec. Shower | Water heating frequency of usage during winter: 1 (daily); 2 (few times per week); 3 (few times per month); 4 (never) |
| **Energy-Related Outcomes** | |
| Av. En. Daily | Average daily energy consumption (kWh) from February to July: gas and electricity (kWh) |
| Av. Temp. | Average temperature of living room and kitchen from February to May (ºC) |
| Temp. TC. | Percentage of time the average temperature was inside the thermal comfort range as defined in EN15251 (European Commission, 2006) from February to May (%) |
| Av. RH | Average relative humidity of living room and kitchen from February to May (ºC) |
| RH. TC. | Percentage of time the average relative humidity was inside the thermal comfort range as defined in EN15251 (European Commission, 2006) from February to May (%) |
| Mould | Is there a presence of mould within the house: Yes; No |

**Table 4**
Pre-retrofit performance of households across all three ECF categories. Refer to Table 3 for explanations and units for each indicator.

| Case # | 1 | 3 | 2 | 4 | 5 | 8 | 7 | 11 | 10 | 13 | 14 | 15 | 16 | 17 | 19 | 12 | 20 | 22 | 21 | 23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Household characteristics | | | | | | | | | | | | | | | | | | | | |
| # Occupants | 4 | 4 | 8 | 3 | 1 | 2 | 2 | 4 | 5 | 3 | 4 | 4 | 5 | 2 | 5 | 4 | 4 | 4 | 5 | 5 |
| # Children | 3 | 3 | 6 | 1 | 0 | 0 | 0 | 3 | 4 | 1 | 3 | 3 | 3 | 1 | 3 | 3 | 2 | 2 | 3 | 3 |
| Gender | 2F,2M | 3F,1M | 5F,3M | 2F,1M | 1M | 1F,1M | 1F,1M | 4F | 3F,2M | 1F,2M | 4F | 2F,2M | 2F,3M | 2F | 3F,2M | 3F,1M | 2F,2M | 3F,1M | 2F,3M | 3F,2M |
| Empl. Status | 3 | 1 | 1 | 1 | 1 | 5 | 2 | 1 | 1 | 2 | 2 | 3 | 1 | 3 | 6 | 2 | 1 | 1 | 1 | 1 |
| Hours Occ. | 24 | 24 | 24 | 24 | 20 | 24 | 24 | 24 | 22 | 24 | 20 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 |
| HH Income | 17 | 20 | 37 | 36 | 17 | 22 | 17 | 30 | 66 | 18 | 20 | 25 | 33 | 14 | 23 | 19 | 29 | 30 | 34 | 43 |
| Material conditions | | | | | | | | | | | | | | | | | | | | |
| Constr. Year | 94 | 94 | 94 | 94 | 94 | 94 | 94 | 94 | 94 | 00 | 00 | 00 | 00 | 00 | 00 | 00 | 00 | 00 | 00 | 00 |
| Terrace Pos. | Mid | Mid | Mid | Mid | End | End | End | End | End | Mid | Mid | Mid | Mid | End | End | End | End | SD | SD | SD |
| Orientation | E | E | W | W | S | N | W | W | W | S | S | S | W | S | SW | SW | S | SW | W | SW |
| Ext. Walls | HB | HB | HB | HB | HB | HB | HB | HB | HB | CW | CW | CW | CW | CW | CW | CW | CW | CW | CW | CW |
| Attic Insul. | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Window | P-6 | P-6 | P-6 | P-6 | P-6 | P-6 | P-6 | P-6 | P-6 | W-6 | W-6 | W-6 | W-6 | W-6 | W-6 | W-6 | W-6 | W-6 | W-6 | W-6 |
| Boiler Effic. | 79 | 79 | 79 | 79 | 91.8 | 79 | 88.5 | 91.8 | 79 | 77 | 77 | 77 | 77 | 77 | 77 | 77 | 90.9 | 77 | 77 | 88.4 |
| Boiler Pow. | 11.72 | 11.72 | 11.72 | 11.72 | 19.5 | 11.72 | 15 | 19.5 | 11.72 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 22 | 10 | 10 | 18.0 |
| 2nd Heating | OF | N/A | GF | EF | OF | OF | GF | EF | OF | GF | EF | OF | OF | OF | EF | EF | EF | ST | EF | OF |
| # Appliances | 8 | 13 | 11 | 12 | 12 | 13 | 8 | 6 | 20 | 11 | 13 | 9 | 11 | 9 | 11 | 13 | 12 | 12 | 19 | 15 |
| Ventilation | B | B | B | B | B | B | B | B | B | A | A | A | A | A | A | A | A | A | A | A |
| Air-Perm. | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | 8.94 | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Attitudes, perceptions and social norms | | | | | | | | | | | | | | | | | | | | |
| Th. Comfort | VD | VD | VD | D | VD | S | VD | D | VD | D | D | D | D | VD | VD | VD | S | S | VD | D |
| Nec. v Lux. | 1 | 1 | 1 | 2 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 2 | 2 | 1 | 3 | 1 | 1 | 1 |
| Benefit | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 1 | 2 | 1 | 1 | 2 | 2 | 1 | 2 | 1 | 2 | 1 |
| Incentives | 1 | 1 | 1 | 1 | 3 | 2 | 1 | 2 | 2 | 3 | 3 | 2 | 1 | 1 | 2 | 3 | 2 | 1 | 1 | 1 |
| Env. Att. | 35 | 39 | 36 | 44 | 34 | 39 | 33 | 36 | 35 | 38 | 33 | 33 | 37 | 32 | 36 | 34 | 33 | 29 | 32 | 32 |
| Practices (February-July 2015) | | | | | | | | | | | | | | | | | | | | |
| CH Freq. | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| CH Set. | P/M | P/M | P/M | M | P/M | P/M | M | P/M | P/M | M | P/M | M | M | M | P/M | P/M | P/M | M | M | P/M |
| WH Freq. | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| WH Sec. | Yes | No | No | Yes | No | No | No | No | Yes | Yes | Yes | No | No | No | Yes | Yes | No | Yes | No | No |
| Hrs Lights on | 14 | 6 | 14 | 6 | 3 | 14 | 14 | 14 | 14 | 6 | 14 | 6 | 6 | 14 | 6 | 14 | 11 | 24 | 14 | 14 |
| Dishwasher | 0 | 2 | 3 | 2 | 2 | 2 | 0 | 0 | 3 | 3 | 0 | 0 | 0 | 3 | 3 | 2 | 3 | 3 | 0 | 3 |
| W. Machine | 3 | 3 | 3 | 0 | 2 | 2 | 2 | 3 | 2 | 3 | 2 | 3 | 2 | 3 | 2 | 2 | 3 | 3 | 3 | 3 |
| Tum. Dryer | 0 | 1 | 3 | 0 | 1 | 2 | 2 | 2 | 1 | 0 | 0 | 3 | 0 | 2 | 1 | 0 | 1 | 0 | 0 | 3 |
| Elec. Shower | 0 | 3 | 0 | 3 | 0 | 3 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 3 | 3 | 3 | 0 | 0 | 3 |
| Energy-Related Outcomes | | | | | | | | | | | | | | | | | | | | |
| Av. En. Daily (Fe-Ju) | 26 | 35 | 34 | 41 | 27 | 34 | 44 | 47 | 50 | 27 | 25 | 36 | 40 | 19 | 28 | 32 | 48 | 33 | 33 | 58 |
| *Gas* | 15 | 24 | 21 | 25 | 20 | 27 | 28 | 38 | 33 | 17 | 16 | 20 | 27 | 10 | 18 | 22 | 31 | 20 | 18 | 42 |
| *Electricity* | 11 | 11 | 13 | 16 | 7 | 7 | 16 | 10 | 16 | 10 | 9 | 15 | 12 | 9 | 9 | 10 | 17 | 12 | 15 | 16 |
| Av. Temp. | 20.2[1,3] | 19.8[2,4] | – | 20.7[2] | 18.3[1] | 20.6[1] | 20.1[2,3] | 20.6[1,3] | 22.0[1] | 18.9[2] | 19.1[1,3] | 18.7[2,4] | 20.3[2] | 16.9[1] | 18.5[1] | – | 20.1[1] | 18.1[1] | – | 21.7[1] |
| Temp. TC | 86 | 93 | – | 96 | 53 | 99 | 99 | 99 | 100 | 87 | 86 | 75 | 96 | 29 | 64 | – | 100 | 61 | – | 100 |
| Av. RH. | 48.4[1,3] | 45.9[2,4] | – | 40.8[2] | 46.7[1] | 46.0[1] | 44.8[2,3] | 40.8[1,3] | 40.0[1] | 48.6[2] | 44.7[1,3] | 50.5[2,4] | 43.8[2] | 59.1[1] | 51.6[1] | – | 48.7[1] | 52.0[1] | – | 42.6[1] |
| RH. TC | 100 | 100 | – | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | – | 100 | 100 | – | 100 |
| Mould | Yes | Yes | Yes | Yes | No | Yes | Yes | No | No | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |

Notes: Temperature and relative humidity data available from the [1]13th February or the [2]27th February.Temperature and relative humidity data available for only [3]living room or [4]kitchen.

**Table 5**
Post-retrofit performance of households across all three ECF categories. Refer to Table 3 for explanations and units for each indicator.

| Case # | 1 | 3 | 2 | 4 | 5 | 8 | 7 | 11 | 10 | 13 | 14 | 15 | 16[a] | 17 | 19[a] | 12 | 20[a] | 22 | 21 | 23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Household characteristics** | | | | | | | | | | | | | | | | | | | | |
| # Occupants | 4 | 4 | 8 | 3 | 1 | 2 | 2 | 4 | 5 | 3 | 4 | 4 | 5 | 2 | 5 | - | 4 | 4 | 5 | 5 |
| # Children | 2 | 3 | 6 | 1 | 0 | 0 | 0 | 3 | 4 | 1 | 3 | 3 | 3 | 1 | 3 | - | 2 | 2 | 3 | 3 |
| Gender | 3F, 1M | 3F, 1M | 5F, 3M | 2F, 1M | 1M | 1F, 1M | 1F, 1M | 4F | 3F, 2M | 1F, 2M | 4F | 2F, 2M | 2F, 3M | 2F | 3F, 2M | - | 2F, 2M | 3F, 1M | 2F, 3M | 3F, 2M |
| Empl. Status | 3 | 1 | 1 | 1 | 1 | 5 | 2 | 1 | 1 | 2 | 2 | 6 | 3 | 3 | 6 | - | 1 | 1 | 1 | 1 |
| Hours Occ.[b] | 21 | 24 | 24 | 22 | 16 | 24 | 24 | 24 | 24 | 24 | 20 | 24 | 23 | 24 | 24 | - | 24 | 22 | 24 | 24 |
| HH Income[c] | 16 | 22 | 37 | 36 | 25 | 22 | 16 | 20 | 66 | 18 | 20 | 24 | 33 | 14 | 30 | - | 29 | 29 | 34 | 43 |
| **Material conditions** | | | | | | | | | | | | | | | | | | | | |
| Ext. Walls | HB | HB | HB | HB | HB | HB | HB | HB | HB | PC | PC | PC | PC | PC | PC | PC | PC | PC | PC | PC |
| Attic Insul. | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 |
| Window | P-16 | P-16 | P-16 | P-16 | P-16 | P-16 | P-16 | P-16 | P-16 | P-16 | P-16 | P-16 | P-16 | P-16 | P-16 | P-16 | P-16 | P-16 | P-16 | P-16 |
| Boiler Effic. | 90.3 | 90.3 | 90.3 | 90.3 | 90.3 | 90.3 | 90.3 | 90.3 | 90.3 | 90.3 | 90.3 | 90.3 | 90.3 | 90.3 | 90.3 | 90.3 | 90.3 | 90.3 | 90.3 | 90.3 |
| Boiler Power | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 |
| 2nd Heating | OF | N/A | GF | EF | OF | OF | GF | EF | OF | GF | EF | OF | OF | OF | EF | - | EF | ST | EF | OF |
| # Appliances | 8 | 13 | 11 | 13 | 12 | 16 | 8 | 9 | 17 | 13 | 12 | 15 | 10 | 11 | 16 | - | 15 | 9 | 13 | 12 |
| Ventilation[d] | C | C | C | C | C | C | C | C | C | C | C | C | C | C | C | C | C | C | C | C |
| Air-Perm. | N/A | N/A | N/A | N/A | 8.75 | 7.28 | N/A | 8.86 | 8.59 | N/A | N/A | 5.93 | N/A | N/A | N/A | - | 5.46 | 5.91 | N/A | 6.36 |
| **Attitudes, perceptions and social norms** | | | | | | | | | | | | | | | | | | | | |
| Th. Comfort[e] | D | VD | D | N | N | VS | S | D | VS | S | S | S | S | VS | S | - | S | VS | D | S |
| Nec. v Lux.[f] | 1 | 1 | 1 | 2 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 2 | 2 | 1 | - | 3 | 1 | 1 | 2 |
| Benefit[g] | 1 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | - | 2 | 2 | 1 | 2 |
| Incentives[h] | 3 | 4 | 2 | 2 | 3 | 2 | 2 | 2 | 1 | 1 | 3 | 2 | 3 | 1 | 2 | - | 1 | 2 | 1 | 2 |
| Env. Att.[i] | 33 | 37 | 34 | 42 | 35 | 37 | 32 | 35 | 31 | 30 | 37 | 37 | 37 | 34 | 36 | - | 29 | 29 | 32 | 32 |
| **Practices (February-July 2016)** | | | | | | | | | | | | | | | | | | | | |
| CH Freq.[j] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | - | 1 | 1 | 1 | 1 |
| CH Set.[k] | P/M | P/M | P/M | P/M | P/M | P | M | M | P/M | M | P/M | P/M | M | M | P/M | | P/M | M | P/M | P/M |
| WH Freq.[j] | 1 | 2 | 1 | 1 | 1 | 1 | 4 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 2 | - | 1 | 1 | 1 | 1 |
| WH Sec.[j] | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | - | No | No | No | No |
| Hrs Lights on[l] | 8 | 7 | 14 | 6 | 6 | 14 | 5 | 15 | 6 | 7 | 15 | 6 | 6 | 14 | 6 | - | 14 | 24 | 14 | 14 |
| Dishwasher[j] | 0 | 2 | 3 | 2 | 2 | 2 | 0 | 0 | 3 | 3 | 0 | 0 | 0 | 3 | 3 | - | 3 | 3 | 0 | 3 |
| W. Machine[j] | 2 | 3 | 3 | 0 | 2 | 2 | 3 | 3 | 2 | 3 | 2 | 3 | 2 | 3 | 2 | - | 3 | 3 | 3 | 3 |
| Tum. Dryer[j] | 0 | 1 | 3 | 0 | 2 | 2 | 1 | 2 | 1 | 0 | 0 | 3 | 0 | 2 | 1 | - | 2 | 0 | 2 | 3 |
| Elec. Shower[j] | 0 | 3 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 3 | - | 3 | 0 | 0 | 3 |
| **Energy Related Outcomes** | | | | | | | | | | | | | | | | | | | | |
| Av. En. Daily[m] | 18 | 27 | 30 | 27 | 24 | 23 | 39 | 36 | 36 | 24 | 22 | 26 | 35 | 20 | 25 | 25 | 36 | 33 | 31 | 41 |
| *Gas*[m] | 11 | 18 | 18 | 19 | 16 | 16 | 26 | 27 | 24 | 15 | 14 | 13 | 22 | 10 | 16 | 13 | 20 | 22 | 19 | 25 |
| *Electricity*[m] | 8 | 9 | 12 | 8 | 8 | 7 | 12 | 9 | 12 | 9 | 8 | 14 | 12 | 9 | 10 | 12 | 16 | 11 | 12 | 16 |
| Av.Temp.[n] | 20.3[1,3] | 20.6[2,4] | - | 19.2[2] | 19.1[1] | 19.7[1] | 21.0[2,3] | 20.4[1,3] | 21.7[1] | 20.1[2] | 19.9[1,3] | 17.2[2,4] | 20.7[2] | 19.4[1] | 20.2[1] | - | - | 19.8[1] | - | 22.6[1] |
| Temp. TC[o] | 93 | 96 | - | 82 | 72 | 96 | 100 | 100 | 100 | 97 | 99 | 46 | 99 | 89 | 100 | - | - | 96 | - | 100 |
| Av. RH.[n] | 48.8[1,3] | 49.2[2,4] | - | 45.5[2] | 46.3[1] | 46.1[1] | 45.1[2,3] | 42.7[1,3] | 46.2[1] | 48.3[2] | 45.7[1,3] | 54.2[2,4] | 47.9[2] | 52.2[1] | 47.2[1] | - | - | 48.7[1] | - | 45.7[1] |
| RH. TC[o] | 100 | 100 | - | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | - | - | 100 | - | 100 |
| Mould[p] | Yes | No | Yes | No | No | No | No | Yes | Yes | No | Yes | No | No | Yes | No | - | Yes | Yes | No | No |

Notes:[a]Change of respondent between pre-retrofit and post-retrofit surveys. Blue highlights show changes from pre-retrofit to post-retrofit for household characteristics: [b] > 1 h; [c] > €1k. Grey highlights indicate changes from pre-retrofit to post-retrofit for: [d]change in ventilation elements; [f]opinion on appliance necessities and luxuries; [g]incentives to encourage retrofitting; [h]benefits from retrofit and [k]change in space heating method.Green highlights indicate positive pre-retrofit to post-retrofit changes: [e]Change in thermal comfort; [i] > 2 points up; jreduction in energy intensive practice; [l] > 1 h up; [m] > 6 kW h (total) / 4 kW h (gas) / 2 kW h (electricity) down; [n]statistically significant increase in average temperature or relative humidity; [o] > 5 %; [p]reduction in mould. Red highlights indicate negative pre-retrofit to post-retrofit changes: [e]Change in thermal comfort; [i] > 2 points down; j increase in energy intensive practice; [l] > 1 h down; [m] > 6 kW h (total) / 4 kW h (gas) / 2 kW h (electricity) up; [n]statistically significant decrease in average temperature or relative humidity; [o] < 5 %; [p]increase in mould. Temperature and relative humidity data available from the [1]13th February or the [2]27th February.Temperature and relative humidity data available for only [3]living room or [4]kitchen.

#### 4.1.1. Household characteristics

This study involved householders with particular employment characteristics, income levels and occupancy numbers, which may affect their responses to retrofitting. Householders' incomes ranged from €14,100 to €65,800. The median real disposable household income in Ireland is €44,782 (CSO, 2017). The rent of householders living in houses constructed in 1994 increased by €3 per week for five years after the houses were retrofitted. Due to more insulation installed in the external walls of the houses built in 2000 during the retrofit works, the householders living in these houses had a rent increase of €6 per week for five years. This rent increase was to pay for the energy efficiency retrofit works in combination with a grant received through the SEAI Better Energy Communities grant programme (SEAI, 2018a). This was not represented in the household income indicator as this represents householders' net income. Working in the service sector (35 %), unemployment (20 %) and looking after the home (15 %) represented the head of household status for a significant portion of households. 17 households stated that on an average weekday, there was someone present in the house 24 h a day. In all, there were 78 residents (48 female and 30 male) living in the houses, mostly in households of four or five people. Those under 14 years of age represented the largest age group, followed by the category 36–45 years old. 16 of the 20 households have lived in their house for 10 years or more, which suggested that many householders could be particularly routinised in their domestic practices. There were changes for some households in terms of household income and average number of hours the building was occupied in the follow up post-retrofit survey. However, any change in the household characteristics indicators used were not directly related to the energy efficiency retrofit works.

#### 4.1.2. Material conditions

Changes to the building structure and primary heating system were directly related to the energy efficiency retrofit works. Prior to the retrofit works, many householders complained of heat loss, uncomfortably cool indoor temperatures, excess drafts entering via badly sealed windows and doors, condensation on windows and mould growth around window framing and junctions of walls and ceilings. To address these issues, energy efficiency retrofit works included pumped cavity wall insulation, attic insulation, double-glazed uPVC-framed windows, uPVC-framed front door, uPVC-framed back patio doors and heating system and controls. In addition, to help combat the issue of mould growth within the houses and provide clean, fresh air to the

householders, mechanical extract fans were installed in the kitchen and bathroom of each house. Furthermore, passive vents were installed in each room of the houses constructed in 2000 and existing vents were cleaned in the 1994 houses. All the new windows had passive vents along the edging of the window frames.

The impact of workmanship can also be found in the air permeability results of the houses post-retrofit. An air permeability test measures the air leakage rate per hour per square meter of building envelope area at a test reference pressure differential across the building envelope of 50 Pa. Eight of the 20 households had air permeability tests carried out post-retrofit by an independent contractor. For the end-terraced and semi-detached houses constructed in 2000, theoretically they should have the same level of air-permeability. However, the results ranged from 5.46 $m^3/(hr.\ m^2)$ to 6.36 $m^3/(hr.\ m^2)$. For the 1994 end terraced houses, the air permeability post-retrofit test results ranged from 7.28 $m^3/(hr.\ m^2)$ to 8.86 $m^3/(hr.\ m^2)$.

The pre-retrofit number of appliances in each of the 20 households varied between 6 and 20 and it was possible to detect some significant post-retrofit changes (e.g. Case 12 gained six appliances, while Case 19 lost six). However, only one household increased the number of high-energy usage appliances.

#### 4.1.3. Attitudes, perceptions and social norms

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

However, some noted that the issue of drafts had not been entirely eradicated when answering the survey question regarding their satisfaction with the installed retrofit measures. Some felt that drafts were still entering their houses through poorly sealed windows and doors, particularly on windy days. The new vents that had been installed also came in for criticism regarding drafts. Issues with post-retrofit drafts from vents in Irish residential buildings leading to householders blocking or closing vents have also been found in another Irish building retrofit study (Sinnott, 2016).

Another issue some householders had with the energy efficiency retrofit technology installed in their houses was the functionality of the new gas boiler heating system. Using the old gas boiler heating system, the householders could operate the space heating and domestic hot water heating system simultaneously. With the new gas boiler heating system, this was no longer possible. If both the space heating and domestic hot water heating systems are operated simultaneously, the domestic hot water takes precedence over the space heating. This constraint meant that householders had to adapt their approach to operating their heating system.

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

Concerning incentives, participants predominantly chose economic incentives (84 % pre-retrofit, 74 % post-retrofit) as the best way to encourage people to save energy. Following the retrofit, there was a marked shift away from a preference for grants to lower utility bills. This most likely reflects the fact that grants incentivise once-off pro-environmental behaviour (such as a retrofit, which the participants have already undertaken), while lower utility bills can be achieved by practicing more habitual pro-environmental behaviour (Lavelle, Rau, & Fahy, 2015).

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

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

#### 4.1.4. Practices

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

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

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

#### 4.1.5. Energy-related outcomes

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

by more than 6 kW h/day. After the retrofit, 17 of the households reduced their gas energy consumption with 11 households decreasing their average daily gas consumption by more than 4 kW h/day. 16 of the households reduced their electricity use, with 6 of the households decreasing their average electricity energy consumption by more than 2 kW h/day.

There was a 23 % decrease in the average gas consumption to 18.2 kW h/day. Ideally, this analysis would have a control group of houses that did not receive energy efficiency retrofit measures to compare their change in energy use, attitudes, perceptions and social norms between 2015 and 2016. Unfortunately, this was not feasible. However, 17 of the 20 houses experienced a reduction in HDD-corrected gas energy consumption. This reduction in energy consumption by the participating households contrasts with an increase in Ireland's residential energy consumption in 2016 compared to 2015 and 2014 (SEAI, 2018b). Therefore, the change in gas energy consumption was likely due to the retrofit works. While the gas energy consumption reduced overall, there remained a substantial range between the lowest and highest gas users and the energy savings for each of the householders.

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

10 of the case studies increased their average temperature by a statistically significant margin. The largest temperature increase was in Case 17 which experienced a temperature increase of 2.5 °C. Case 15 had the largest temperature decrease, dropping by 1.6 °C. Households that increased their temperature experienced an increase of, on average, 1.1 °C and those who dropped in temperature experienced a decrease of, on average, 0.8 °C. On average, households increased their temperature by 0.4 °C. Other temperature change studies from energy efficiency building retrofits (Dinan, 1987; Fowlie et al., 2015; Henderson et al., 2003; Hirst, White, & Goeltz, 1985; Martin & Watson, 2006; Milne & Boardman, 2000; Oreszczyn, Hong, Ridley, & Wilkinson, 2006; Schwarz & Taylor, 1995) found the average change (excluding confidence intervals) in house temperatures ranged from -0.3 °C to 2.8 °C with the (i) type of energy efficiency retrofit, (ii) room of house that was monitored, (iii) period analysed, (iv) heating system employed, (v) household income levels and (vi) householder comfort impacting the level of change in temperature.

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

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

Issues of mould along the junctions of ceilings and walls persisted. Due to the building element construction details used in the houses constructed in 1994 and 2000, the junctions of the external walls with other building elements had thermal bridging issues. Unless householders were diligent with their heating and ventilation strategies to prevent the build-up of moisture in their houses, the moisture in the air would condense on the cold spots along the junctions of the walls with other building elements, leading to mould growth. The quality of the workmanship for constructing or installing building materials can also lead to thermal bridging.

### 4.2. Interplay of ECF indicators, energy consumption and energy savings

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

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

The perception of what is a satisfactory thermal comfort level can vary from household to household. For example, the average house temperature for three of the 10 households who were very dissatisfied with their thermal comfort did not fall outside the temperature thermal comfort limit as defined in EN15251 (European Commission, 2006) before the retrofit (> 1 %) (Cases 2, 7 and 10). The perception of what is a satisfactory thermal comfort level may have also influenced the success of the retrofitting efforts in reducing energy consumption. Cases 7 and 8 were (i) 1994 end-terraced housing, (ii) had similar gas consumption and average house temperatures pre-retrofit and (iii) both had two people living in the house. However, the two houses differ on whether they were satisfied with their thermal comfort level. The householders in Case 8 were satisfied pre-retrofit with their thermal comfort level. These householders achieved the second highest gas energy reduction while also slightly reducing their average house temperature. The householders of Case 7 were very dissatisfied with their pre-retrofit thermal comfort level. Following changes to the material conditions, the average house temperature increased by 0.9 °C and the household achieved only the 16$^{th}$ highest gas reduction.

Methods of how householders operated their space heating system persisted in many of the households following the retrofit. The hierarchy of houses in terms of gas and electricity energy consumption levels also remained relatively unchanged (that is, hierarchy position of a given household changed by less than 3 positions) for many of the houses following the energy efficiency retrofit works. Householders changing how they operated their space heating system following the energy efficiency retrofit appeared to have a large impact in terms of the hierarchy of energy consumption among householders. The gas consumption hierarchy position changed by more than 3 places for five households. Interestingly, three of these five households altered how their space heating system was operated (one of the five households included Case 12 where no post-retrofit survey was carried out).

The functionality of the new gas boiler heating system whereby both the space heating and domestic hot water heating could not be heated simultaneously led to five households believing this constraint meant they were operating their new gas boiler system more than with the old gas boiler system. Of the five households who believed they were using the gas boiler more, three households reduced their gas consumption post-retrofit by more than 4 kW h/day (Cases 1, 11 and 20), one household's gas usage reduced by 3.7 kwh/day (Case 5) and one household's gas usage increased by 1.4 kW h/day (Case 21). Unfortunately, the indoor temperature of Case 21 post-retrofit is unavailable to check whether their increased gas usage led to a higher

indoor temperature. However, without comprehensive monitoring of the gas boiler disaggregated energy usage profile before and after the retrofit works, it is difficult to assess whether the new functionality of the heating system impacted the energy savings potential of the householders.

In terms of the hierarchy of electricity consumption, seven households changed position by more than 3 places with four of the seven households not using their electrical immersion to heat their water anymore. Before the retrofit works, the householders of Case 4 found that it was quicker to use the electrical immersion rather than relying on the gas boiler to heat the hot water. Changing the material condition of the gas boiler from 11.7 kW to 17.8 kW allowed the householders to stop using the electrical immersion for heating the water. The householders of Case 4 also stopped using their electric immersion and removed their electrical shower when they discovered the amount of electricity it used. They discovered this from the feedback they received from an electricity consumption in house display installed in their home.

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

## 5. Discussion and conclusions

### *5.1. Using the ECF for interdisciplinary research to investigate retrofitting programmes: advantages and drawbacks*

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

Concerning drawbacks, defining clear boundaries between energy cultures at different scales (e.g. household energy cultures vis-à-vis community energy cultures) can be difficult. For example, some of the systemic influences on energy cultures outlined in Fig. 1 only acquire the label 'systemic' if the focus of the work lies on energy cultures located at the supranational level. If one were to compare national-level energy cultures, some of these would probably be absorbed into the ECF.

Second, the distinction between the three constitutive elements may be less clear-cut given the close interactions between them. For example, prevailing norms concerning the meaning and use of particular appliances (e.g. dishwasher, smartphone) are directly related to their availability (material conditions), and vice versa (Wilhite et al., 2000). Third, the related issues of energy use *outside* the home are particularly pertinent if treated as part of the picture. In fact, it is entirely unclear whether financial savings made by householders following the retrofitting of their homes are spent on more or less energy-intensive activities. For example, some householders may eventually spend their post-retrofit savings on goods and services that require significant input of energy and other resources (e.g. car, foreign holiday). Only an overall cultural shift that extends beyond energy to include other types of resource use (e.g. water, food, plastics) could prevent this. However, there is no evidence that such a shift has occurred following the retrofitting assessed in this analysis.

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

### *5.2. Changing energy cultures? Critical reflections concerning the use of the ECF in pre-retrofit and post-retrofit assessments*

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

There was no marked shift in other areas of energy culture, however, pointing to the relative resistance to change of attitudes and social norms and well-established routine practices. In fact, there is some indication that many householders maintained many of their daily practices after the retrofit, including the use of lighting and appliances. For space and domestic hot water heating, householders had to adapt to the functionality of the new gas boiler heating system. While the new system forced the householders to operate the space and hot water heating separately, many of them continued to rely upon the same way of operating the heating system by either a manual or a set programme in combination with a manual approach. This said, some householders switched their water heating practices from the electric immersion to the gas boiler. In sum, changes in material conditions (retrofit) did

indeed bring about modest changes in practices and related patterns of energy use; however, the retrofit certainly did not shift prevailing energy cultures in any fundamental way.

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

In this paper, the focus was on the energy cultures and their energy-related outcomes across 20 households in a co-operative social housing development in Ireland. External influences (Fig. 1) prevented householders from changing their energy cultures were not included as it was not the focus of the paper. For the households involved in the study, the association which own the housing units play a role in the householder's material conditions. The co-operative housing association which own the housing units applied for the retrofit grant which paid for the majority of the retrofit work. The housing association did not give any of the householders a choice in getting the retrofit or what retrofit technology was installed. Furthermore, some householders stated they were interested in installing energy saving measures to their homes before the energy retrofit work. However, the householders did not as they do not own the house and are not allowed to make any alterations to the exterior of the building ruling out some potential energy saving measures. A common problem with householders in rented housing (Scott et al., 2016). Examining the role landlords and property managers play in limiting householders in rented housing investing in energy efficiency measures could be the focus of future research.

In addition, future application of the ECF could be to identify potential reasons for the shortfall in energy saving predicted by engineering models. For example, for the set of households analysed in this study, the Dwelling Energy Assessment Procedure (DEAP) (SEAI, 2012), which is the assessment procedure for calculating and rating the energy performance of Irish housing units, would not account for householders changing their water heating habits by not using the electric immersion anymore in estimating energy savings. For five of the eight households who stopped using their electrical immersion, their gas consumption during the non-heating season months increased despite the installation of a more energy-efficient gas boiler and hot water tank. DEAP also calculates the energy demand of houses based on a calculated internal temperature profile. Cases 13, 14 and 15 were all mid-terrace 2000 houses with the same orientation and would have similar average temperatures if assessed using DEAP. Nevertheless, the average post-retrofit heating season temperature profiles of these three cases ranged from 17.2 °C to 20.1 °C. Case 22 and 23 were built side by side, yet their average temperatures during the post-retrofit heating season were 19.8 °C and 22.6 °C, respectively.

In summary, the results of this research find that:

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

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

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

Despite these limitations, the ECF helps to capture empirically how changes in one of the elements of energy culture – in this case altered material conditions brought about by an energy retrofitting programme – influence other elements of energy culture and the influence energy culture elements have on household energy consumption and the internal environment. Although the small sample size of this study cannot justify adopting a sociotechnical approach to retrofitting programmes, it adds to the growing calls for such an approach to be implemented for energy savings to be realised (Gianfrate, Piccardo, Longo, & Giachetta, 2017; Gupta, Gregg, Passmore, & Stevens, 2015). If a culturally sensitive sociotechnical approach is applied on a national scale in retrofit projects, it could help to (i) strengthen the evidence for policy-makers in building retrofitting, (ii) inform future targeted building retrofit and environmental mitigation policy measures for different groups of buildings and people, including economically vulnerable parts of the population, (iii) develop hands-on change initiatives and demonstrator projects that seek to transform both householders' attitudes, perceptions and social norms as well as their daily practices and (iv) draw attention to energy-cultural diversity to aid countries in meeting their energy efficiency and carbon reduction targets, including EU member states committed to implementing the EU's Energy Union.

## Declaration of Competing Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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