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Recession or retrofit: an ex-post evaluation of Irish residential space heating trends

Highlights

- Macroeconomic variables included in decomposition analysis to identify recession impacts
- Ex-post energy-efficiency analysis with greater disaggregation than commonplace
- Impacts of fuel switching and technology efficiency progress are explicitly quantified
- Retrofit savings shown to comprise a small proportion of total top-down energy savings
- Future challenge to capture recessionary behavioural changes without economic hardship

Keywords: energy efficiency, exergy, fuel switching, retrofit, NEEAP savings, LMDI-I, top-down, bottom-up.

Abstract

1 Analysis of the technical potential for energy efficiency often highlights very large potential savings; however,
2 the reality of savings achieved often falls far short of this potential. Ex-post analysis is known to be important for
3 quantifying realised energy-efficiency savings, but is often neglected for many reasons. This paper describes an
4 approach to an ex-post analysis that uses readily available administrative data and provides insights into the impact
5 of an energy-efficiency policy measure of residential energy-efficiency retrofitting (upgrades). Ex-post analyses
6 have the advantage of including the impacts of events and behaviours that coincide with energy-efficiency
7 programs and thus facilitate disentangling external influences and avoidance of misattribution of savings. Three
8 different quantitative approaches are used to determine whether the national energy-efficiency retrofit
9 programmes or the economic recession was responsible for the sharp fall in residential space-heating energy
10 demand in Ireland between 2007 and 2012. The analysis finds that while Government energy-efficiency
11 retrofitting programmes have played a role in reducing energy consumption, the biggest influence by far between
12 2007 and 2012 was the economic recession. The top down decomposition analysis recorded energy savings
13 (including ‘savings’ that were due to the recession) that were 3.9 times greater than bottom-up retrofit savings
14 related to residential space-heating measures over the period 2006 - 2012. The analysis highlights that an important
15 policy challenge is to achieve reduced consumption due to behavioural changes while experiencing economic
16 growth.

1 Introduction

17 The objective of the analysis in this paper is to determine the extent to which an economic recession and national
18 residential energy-efficiency retrofit programmes influenced historical space-heating trends in Ireland. This paper
19 comprises a robust ex-post quantitative analysis to appraise the impact of a flagship energy-efficiency policy
20 measure, namely residential retrofitting.¹ Ireland was chosen as the case study for this analysis as it has a relatively
21 large space-heating demand and it was affected significantly by the global economic recession, especially relative
22 to other countries in the EU, i.e. Greece, Italy, Spain and Portugal that were also affected significantly by the
23 global recession. The insights should be of interest to an international audience, as residential retrofitting is a
24 policy central to energy-efficiency savings in many countries.

25 The approach adopted in this paper demonstrates how readily available data can be used to quantitatively evaluate
26 the impact of energy-efficiency retrofit programs. A novel approach was used to disaggregate energy efficiency
27 into constituent parts comprising building envelope, fuel switching and technology efficiency components and
28 including macroeconomic variables. The paper identifies the driving forces underlying residential space-heating
29 energy demand using this decomposition analysis. It isolates the impact of the economic recession and the national
30 energy-efficiency retrofit scheme to reveal for the first time the reasons for the reduction in climate-corrected
31 energy consumption between in Ireland 2007 and 2012.

32 Section 2 reviews recent relevant peer-reviewed literature. Section 3 of this paper provides a brief background of
33 the policy context for this analysis. Section 4 describes the methodologies employed and section 5 provides an
34 overview of the data available. Section 6 presents the results of a decomposition analysis, compares these top-
35 down results to bottom up energy-efficiency estimates and examines counterfactual scenarios without retrofit
36 efficiency improvements quantified for the Irish National Energy Efficiency Action Plan (NEEAP). Section 7
37 provides further context for interpretation and discussion of those results. Section 8 summarises and concludes.

2 Literature review

38 This paper aims to isolate the impact of the economic recession and the national energy-efficiency retrofit scheme
39 to better understand the drivers behind the fall in climate-corrected energy consumption between 2007 and 2012.
40 A decomposition analysis facilitates an understanding of the impact of various drivers of energy consumption by
41 means of a quantitative analysis and isolation of the multiple factors involved.

¹ Energy-efficiency retrofitting is also often referred to as energy-efficiency upgrades, but referred to as retrofitting in this paper.

42 The decomposition analysis methodology chosen for this paper was the Logarithmic Mean Divisia Index I
43 (LMDI-I). Rogan et al. provide a definitive list of 5 points on the advantages of LMDI-I (Rogan et al., 2012).² An
44 advantage of LMDI-I in the context of this paper is the ability to easily convert from additive (absolute numbers)
45 to multiplicative (index or percentage change) and vice versa (Ang, 2004). A disadvantage of the LMDI-I
46 methodology is that it cannot be used where there are zeros or negative values in a database, due to the logarithmic
47 functions in the equations. However, there are neither zeros nor negative values in the database used for the
48 analysis in this paper. While LMDI-I is still often quoted as difficult to understand or interpret (Mishina and
49 Muromachi, 2012; IEA, 2014a; Edelenbosch et al., 2017), the strong theoretical foundation (Ang and Liu, 2001,
50 Granel, 2003; Ang, 2012) was determined to outweigh that disadvantage for the analysis in this paper. Other
51 studies have also concluded that LMDI-I is the preferred decomposition analysis method (Ma & Stern, 2008; Ang,
52 2015; Economidou, 2017).

53 Xu and Ang (2014) published a paper on decomposition analysis of the residential sector in 2014, which included
54 a table summarising previous decomposition analyses for the residential sector. A breakdown of energy
55 consumption by fuel in the residential sector, which is the method proposed in this paper, was only used in one of
56 the twenty residential decomposition analysis studies identified by Xu and Ang (2014).

57 There have been numerous examinations of decomposition analysis in the residential sector in Ireland (Rogan et
58 al., 2012; ODYSSEE-MURE, 2015a; SEAI, 2018a) and internationally (IEA, 2014a&b; Economidou, 2017). All
59 these examples can be considered as top-down analysis of the residential sector, as they are based on aggregate
60 energy consumption and residential stock data i.e. top-down analysis. However, none of these examples of
61 decomposition analysis investigated space heating by fuel and technology efficiency.

62 Residential energy-efficiency policy measures are predominantly evaluated using bottom-up analysis methods,
63 specifically based on unit consumption estimates of individual dwellings or dwelling archetypes. Bottom-up
64 analysis often ends up relying on engineering estimates rather than measured data. However, these engineering
65 estimates ignore the fact that space-heating consumption is influenced by a heterogeneity of habits, differences in
66 heating practices, lifestyles, attitudes, energy prices, and income levels (Haas, 1997). Levels of affluence are also
67 important as they tend to be associated with increasing levels of comfort (Ó Broin, 2007). In contrast to bottom-
68 up engineering estimates of policy impacts, a top-down ex-post analysis (which reflects actual usage) will capture
69 the impact of any energy-efficiency improvements as well as the impact of behaviour.

² The points are: 1. LMDI-I is a perfect decomposition analysis methodology (i.e. no remainder) 2. Transparency, as the additive form presents results in energy units 3. The LMDI-I formula does not increase in complexity as the number of effects analysed expands 4. The formula are consistency-in-aggregation 5. LMDI-I has a strong theoretical foundation.

70 Recent analysis on Irish houses that use the bottom-up modelling software Dwelling Energy Assessment
71 Procedure (DEAP) for generating a Building Energy Rating certificate (BER), suggest that DEAP overestimates
72 heating schedules and room temperatures by up to 37% and 1°C respectively compared to measured data using
73 sensors in dwellings (Hunter et al., 2017). Thus bottom-up estimates of energy efficiency improvements based on
74 DEAP, such as used in the NEEAP, are likely to overestimate energy efficiency savings. Another interesting
75 finding from Hunter et al. is the extent to which secondary heating is used; in the oil-fired homes included in the
76 study more than 50% indicated their preference to use a secondary heating source on all or most days. However,
77 the Hunter et al. study only had a very small sample size of 67 retrofitted oil-fuelled dwellings.

78 There have been other evaluations of the Irish retrofit schemes with bigger sample sizes. In Scheer et al. (2013),
79 an ex-post billing analysis of 210 dwellings partaking in the Home Energy Savings Scheme between 2008 and
80 2010, concluded that energy efficiency upgrades led to an estimated 21% saving (natural gas only). Notably, a
81 shortfall of approximately 36% ($\pm 8\%$) was quantified between the ex-ante technical potential as projected using
82 engineering estimates and the measured ex-post savings. More recent analysis, such as Collins and Curtis (2017),
83 has focused on financial impacts rather than quantifying energy savings or the impact on energy demand. Other
84 analysis has suggested that the motivation for applying for grants is more likely to be greater comfort levels, than
85 achieving energy-efficiency savings (Byrne et al., 2016).

86 In a top-down ex-post analysis, as the impact of behaviour is inherently captured in the dataset any
87 energy-efficiency improvements reflects actual usage. Exergy analysis helps to understand the final energy
88 demand independent of the technology mix and identify opportunities to accelerate the transition to higher quality
89 cleaner fuels based on thermodynamic principles (IEA, 2007). Exergy analysis is commonly used for the purpose
90 of designing, optimising or controlling specific technologies, processes or systems. A building exergy analysis
91 tool (termed Low Exergy Systems for Heating and Cooling of Buildings - LowEX), was developed as part of the
92 International Energy Agency's (IEA) Energy Conservation in Buildings and Community Systems (ECBCS)
93 research collaboration group Annex 37 (IEA ECBCS, 2003). However, LowEx was designed for technical or
94 engineering calculations by architects or engineers at the technology level rather than aggregated actual usage,
95 which is the focus of this paper. For the purpose of this paper, a proxy for exergy, namely useful energy, is
96 calculated as energy demand multiplied by fuel or technology efficiency. A similar approach was adopted by
97 Serrenho et al. (2014), but in this paper there is a focus on residential space-heating demand.

3 Policy context

98 In 2006 the European Union (EU) introduced the Energy Services Directive (ESD) (EU, 2006), which set an
99 indicative target for Member States to achieve a 1% per annum energy-efficiency improvement resulting in a
100 cumulative target of a 9% improvement in energy efficiency by 2016. Member States were also required to prepare
101 a National Energy Efficiency Action Plan (NEEAP) to describe the pathway to achieving the cumulative 9%
102 energy-efficiency improvement target.

103 The Irish NEEAP policy measures that relate to residential space-heating demand can be broadly divided into two
104 categories, namely building regulations or grant schemes. The building regulation category includes a number of
105 revisions to the Building Regulations and energy efficient boiler regulations.³ The grant schemes can be broadly
106 categorised into grant schemes for vulnerable homes, grant schemes for homeowners, grant schemes for
107 communities, grants through energy utilities under the Energy Efficiency Obligations Scheme (EEOS), and also
108 some renewable energy support schemes.^{4,5}

109 While there have been national energy-efficiency retrofit programmes in place since 2000, the longest running
110 programmes are associated with vulnerable homes (those at risk of fuel poverty or those with elderly occupants).
111 Energy-efficiency programmes for all households in Ireland have been in place since 2006, with approximately
112 23% of the total housing stock availing of the grant schemes (SEAI, 2018d).

113 In Ireland to date there have been four NEEAP reports produced by the Department of Communications, Climate
114 Action and Environment (DCCAE). The latest report (NEEAP 4) includes savings to the end of 2016 (DCCAE,
115 2017b). A time series of the NEEAP reported savings are the bottom up energy efficiency savings used in the
116 analysis of this paper.

4 Methodology

117 Most analyses of residential space heating examine the overall change in energy consumption per household or
118 per square metre as a proxy for energy efficiency. In such cases, the impacts of fuel switching and technological
119 improvements are conflated into an overall “efficiency” change. When the impact of fuel switching is conflated

³ Part L of the Building Regulations (Conservation of Fuel and Energy)

⁴ The Warmer Homes Scheme (WHS), more recently branded as the Better Energy Warmer Homes scheme (SEAI, 2018d). The Department of Housing, Planning, Community and Local Government also provide support to vulnerable homes with elderly or disabled occupants (DCCAE, 2017b).

⁵ Approximately 10% of the entire 2016 building stock (203,561 homes) received support from SEAI energy efficiency retrofit schemes (DCCAE, 2017a). The Home Energy Savings scheme and the Greener Homes Scheme (GHS) was in place between 2006 and 2011. In May 2011 the Better Energy Homes (BEH) scheme was launched incorporating the Home Energy Savings scheme, the Warmer Homes Scheme and the Greener Homes Scheme (SEAI, 2018d). An Energy Efficiency Obligations Scheme (EEOS) introduced in January 2014 energy suppliers are mandated to meet specified annual targets every year until 2020 (DCCAE, 2017b). Further homes have been upgraded through the Better Energy Communities scheme that was introduced in 2016 (DCCAE, 2017b).

120 or subsumed into the energy-efficiency improvement metric, results can be misleading, especially as fuel
121 switching is usually in the direction of fuels that can be used more efficiently.⁶

122 The novel approach in this paper is to disaggregate the energy-efficiency indicator into three separate factors,
123 namely useful-energy efficiency (including building envelope and behavioural changes), technology efficiency
124 and fuel switching, as detailed in Equation 1. Where E is total space heating energy consumption, F is total
125 residential floor area measured in metres squared, E_u is useful energy (a proxy for exergy) and i relates to the
126 different fuels or energy sources that make up total residential energy consumption. The right-most term in
127 Equation 1 relates the efficiency of conversion of different fuels or energy sources in useful space heating energy.
128 It is the inverse of the technology efficiency i.e. the inverse of the useful energy divided by the energy for each
129 fuel type.

Equation 1

$$\frac{E}{F} = \frac{E_u}{F} \times \sum_i \frac{E_{u,i}}{E_u} \times \frac{E_i}{E_{u,i}}$$

130 An advantage of the proposed breakdown (by fuel⁷ and also including technology efficiencies) is that the analysis
131 becomes a closer approximation to that of technology and engineering modelling in terms of the datasets and
132 assumptions included. It also facilitates identifying the impacts of readily-available policy levers such as
133 technology-efficiency standards and the incentivisation of certain technologies (e.g. encouraging fuel switching).
134 Another advantage is that the efficiency metric, when based on useful energy, approximates the theoretical concept
135 of exergy.

136 Exergy is a thermodynamic term which relates to the portion of an energy input that is transformed into useful
137 work. i.e. the energy service demand such as heated floor area. As exergy is difficult to quantify and measure, in
138 particular at the level of national energy statistics, it is not often analysed. However, indicators based on exergy
139 or useful energy are a closer approximation to the true efficiency of a system and the work needed to provide a
140 particular energy service.

⁶ Although the recent rise in renewable energy sources is an exception to that generalisation.

⁷ A factor in a decomposition analysis identity equation that does not vary over time will result in a calculation of the natural logarithm of 1 in the LMDI-I equations, which solves to zero i.e. that factor has no impact on the price/energy demand or emissions between the two periods of time or scenarios being examined. In order to include a breakdown by fuel the share of each fuel in total useful energy or exergy is required, as otherwise the energy share will also solve to 1.

141 This paper also examines expanding the number of factors in traditional residential sector space heating analyses
142 to incorporate macroeconomic factors. Total space heating energy consumption comprising eight distinct factors
143 is presented in Equation 2.

Equation 2

$$E = D \times \frac{S}{D} \times \frac{P}{S} \times \frac{Dw}{P} \times \frac{F}{Dw} \times \frac{E_u}{F} \times \sum_i \frac{E_{u,i}}{E_u} \times \frac{E_i}{E_{u,i}}$$

144 Where E is the total energy used for space heating. D is disposable income, S is energy spend on space heat, P is
145 the total population, Dw is the total of permanently occupied dwellings, F representing the floor area in square
146 metres⁸. E_u is useful energy (proxy for exergy) and i relates to the different fuels or energy sources that make up
147 total residential energy consumption.

148 The disposable income term in Equation 2 is the total disposable income in monetary terms in any given year. It
149 is interesting to create a link between energy spend and disposable income as proposed in the second term of
150 Equation 2, even if that spend pertains to all residential energy consumption.⁹ Population is included to monitor
151 the effect of energy spend per person, albeit the reciprocal term (population divided by energy spend) is
152 necessitated in Equation 2. A reciprocal term requires some extra care in the interpretation, but is a necessary
153 inconvenience to achieve the economic link and examine as many factors as possible.

154 Population could be excluded and the third and fourth terms in Equation 2 collapsed into a term related to energy
155 spend per dwelling. Further, combining the second, third and fourth terms in Equation 2 facilitates examining the
156 impact of the variation in disposable income per dwelling. The advantage of analysing many factors as possible
157 is that further refinements can be additionally examined with post-processing of the results, thus compromise on
158 what factors are examined is not necessary and only dictated by data availability.

159 The rationale for including population and floor area is that both the occupancy and dwelling size are known
160 drivers of space-heating energy consumption and are interesting trends worth isolating, especially in the context
161 linking demand to economic activity.¹⁰ All else being equal, a lower occupancy rate nationally (less people per
162 dwelling) will likely result in higher space heating demand, as there are more individuals heating their dwellings.

⁸ There are many different arguments about what is the best measure of energy-efficiency improvements for space heating. While cubic metres are probably the most accurate in terms of actual energy losses, data on the cubic metres of the entire residential stock is not available. Other arguments relate to whether non-heated areas are inadvertently included in national energy statistics, a point which is especially relevant for international comparisons or benchmarking (IEA, 2015).

⁹ It is reasonable to include spend as a variable in the decomposition analysis identity equation as the fuel and power spend excluding motor fuel does not impact on the energy consumption or efficiency estimates. Spend is strongly influenced by space-heating energy consumption and was included in this equation to gauge consumer responses to price changes.

¹⁰ Correlation factor of -.94 for occupancy (number of persons per dwelling) and .97 for dwelling size (floor area per dwelling) for the period 2000 - 2016.

163 Similarly, and all else being equal, a dwelling that is larger will both have a larger area requiring heating and a
164 large area through which heat will be lost, therefore the space heating demand will be higher.

165 The 4th term in Equation 2 (Dw/P) is the inverse or reciprocal of occupancy. As occupancy decreases, which is
166 the current trend in Ireland, the reciprocal term will increase. The dwelling size impact, also a reciprocal term, is
167 quantified from the 5th term in Equation 2.

168 The useful energy-efficiency improvement term (a proxy for exergy efficiency) includes the impact of the building
169 envelope changes, as well as behavioural and rebound effects that cannot readily be measured explicitly. As
170 reliable floor area by fuel type is not available in national energy statistics, and because a lot of dwellings will use
171 different fuels for primary and secondary heating, the useful energy per square metre term is not analysed by fuel.

172 The fuel-share factor ($\frac{E_{u,i}}{E_u}$) can also be thought of as a metric to capture the impact of fuel switching. In the context
173 of this paper the term fuel switching should be interpreted as the aggregate impact of decisions by individual
174 homeowners to switch their main source of heating fuels. Rural dwellings in Ireland and older dwellings in urban
175 areas are more likely to rely on oil central heating, as the gas grid does not reach those areas. This is particularly
176 relevant in the context of fuel switching as changes to fuel shares are more likely to signify a shift from a primary
177 heating source to a secondary or supplementary heating source, with the secondary-heating source usually being
178 a solid fuel based open fire or stove. As supplementary electricity heating cannot be isolated from other appliance
179 usage it is not included in the analysis. The technology efficiency calculations are based on the first law of
180 thermodynamics and are explained in detail in Appendix 2.

181 In order to attribute changes in energy or emissions a decomposition analysis is often employed to understand the
182 underlying factors driving the overall energy consumption or emission trends. Equation 2 can be used as the basis
183 (identity equation¹¹) of a decomposition analysis, to understand the influence of the chosen factors on
184 space-heating energy demand. There are two broad categories of decomposition analysis, namely; index
185 decomposition analysis (IDA) and structural decomposition analysis (SDA). IDA is limited to factors directly
186 included in identity equations, whereas SDA can investigate factors indirectly related to consumption. However,
187 as SDA can only be applied to sectors of the economy for which input output tables are available. Therefore, only
188 IDA is appropriate for analysis of the residential sector.

189 The Logarithmic Mean Divisia Index I (LMDI-I) decomposition analysis, was chosen primarily because of its
190 unique ability to derive additive results from the multiplicative format and vice versa (Granel, 2003). This property
191 is exploited to compare the bottom-up NEEAP estimates to the top-down energy efficiency estimates. The LMDI-

¹¹ An equation describing energy consumption by different constituents is termed an identity equation.

192 I decomposition analysis equations used in the analysis in the results section (section 6) are detailed in Appendix
193 3.

194 A time series of the residential energy-efficiency savings progression over time is included in Appendix 1 (Table
195 A1.1) based on the NEEAP reports and other publicly available sources. The savings can be classified into two
196 groups, namely; building regulations (BRs) and grant retrofit scheme savings (hereafter referred to as retrofit
197 savings). Both the BR and retrofit savings are quantified based on engineering estimates. An evaluation of how
198 the NEEAP savings were calculated is considered beyond the scope of this paper.

199 The NEEAP savings are quantified based on bottom-up engineering estimates by the Sustainable Energy
200 Authority of Ireland (SEAI), the grant scheme administrator.¹² Statistics on the number of households upgraded
201 and energy-efficiency measures installed under the grant scheme are used to calculate the energy and CO₂ savings.
202 The estimated savings are based on assumed efficiency improvements resulting from the installation of approved
203 building fabric and heating system-upgrades in existing dwellings. Savings per-measure and per-dwelling-type
204 are calculated using the DEAP software tool. Final energy savings per dwelling are based on modelled demand
205 reduction from installed measures (actual) since programme inception. Estimates of the BR savings are calculated
206 using statistical information from BER database for existing dwellings to derive the percentage of dwellings with
207 oil or gas boilers that will be replaced by more efficient boilers. Assumptions are made about the boiler lifespan
208 in the absence of boiler installation numbers.

209 As well as a direct comparison of the top-down energy-efficiency savings based on the decompositions analysis
210 and the bottom-up NEEAP energy-efficiency saving, counterfactual scenarios are developed in this paper. These
211 counterfactuals scenarios are calculated by adding the total bottom-up NEEAP energy-efficiency savings to the
212 actual historical residential space-heating demand resulting in a hypothetical demand in the absence of the NEEAP
213 policy measures. The hypothetical demand allows estimates of autonomous space-heating energy-efficiency
214 saving, i.e. estimates of the underlying rate of improvement that would have been recorded in the absence of the
215 NEEAP policy measures.

5 Data availability

216 The Irish energy balances are produced annually by SEAI and include a breakdown by quantity of fuel for the
217 residential sector (SEAI, 2017a). Data are gathered from energy supplier surveys. While the energy balances are

¹² SEAI administer the grant scheme and also estimate the NEEAP savings for all of the residential space-heating related measures.

218 a consistent and reliable data source, gaps remain within these official statistics. Solid fuels such as coal, peat and
219 wood can be stored from year-to-year to a greater extent than other fuels such as heating oil and natural gas, thus,
220 annual usage of those fuels is less certain.

221 A lot of households in Ireland use wood as a secondary or supplementary heating source in open fires, stoves and
222 ranges. Anecdotal evidence suggests strong growth in solid fuel stove installation and use since the economic
223 recession. Estimates of the prevalence of stoves can be gleaned from the BER database (SEAI, 2018b); however,
224 a statistical time series of the installation of solid fuel stove heaters in Ireland is not available. This means that
225 data on secondary or supplementary heating are not accurately reflected in official statistics of space-heating
226 energy demand.

5.1 Energy demand data

5.1.1 Share of fuels used for space heating

227 An energy end-use split of residential sector energy consumption for 2015 and 2016 are available from the SEAI
228 Irish Residential Energy End-Use Model (IREEUM) model, developed to meet European Energy Statistics
229 Regulation (SEAI, 2018a). IREUM is based on the analysis of the BER database, established using a modified
230 version of the DEAP methodology. While the absolute residential consumption and fuel mix in the residential
231 sector has changed rapidly, the end use percentage shares of this energy consumption did not vary significantly
232 between 2000 and 2016 according to SEAI (SEAI, 2018a).¹³ Therefore, for the purposes of this paper general
233 assumptions about the shares of fuels used for space heating are applied to all years based on IREEUM 2015 &
234 2016 shares.

235 For natural gas, non-base load consumption is assumed to represent space heating (Rogan et al., 2012). IREEUM
236 suggests that for natural gas 72% of residential energy consumption is for space heating. The space-heating share
237 in total residential sector fuel consumption increases to 78% for oil-fuelled homes and 95% for solid fuels, while
238 the electricity share is estimated at 10% of residential electricity demand.

239 In this paper all geothermal or ambient energy from heat pumps is considered as space heating use, whereas no
240 solar thermal energy is included, since all but a negligible amount of solar thermal energy is used for domestic
241 hot water heating rather than space heating in Ireland.

¹³ In Europe, a decline of 4 percentage points between 2000 and 2016 in the space-heating share of overall energy demand is quoted in the ODYSSEE-MURE project brochure on Energy in Buildings (ODYSSEE-MURE, 2015b). However, as the analysis in this paper is disaggregated by fuel there is a decline in space heating demand based on the fuel shifts even though the space heating demand share of those fuels is held constant.

5.1.2 *Weather correction*

242 Weather correction is applied to all space-heating consumption to account for year-to-year changes that can
243 significantly impact on demand. Weather (in particular outdoor temperature) has a strong impact on household
244 heating energy. A warm year can result in energy demand reductions not due to energy efficiency, but rather to
245 weather changes. In order to distinguish between energy-demand changes due to weather from other factors
246 (recession, retrofit, etc.) weather correction is applied to the data. SEAI currently apply a population-weighted
247 degree-days methodology for weather correction on an annual basis and that is also the approach adopted in this
248 paper¹⁴. A known consequence of weather correction methodology is to overestimate consumption in mild years
249 and underestimate consumption in cold years¹⁵.

5.1.3 *Technology efficiencies*

250 While there are not sufficiently detailed technology data readily available, existing energy statistics make it
251 relatively straightforward to estimate the impact of fuel switching on space-heating consumption. Appendix 2
252 details the assumptions used to estimate the technology efficiency trends in this paper.

253 By including specific technological details on how the fuels or energy sources in the residential sector are
254 transformed into useful energy, both the impact of fuel switching and technology efficiency changes can be
255 isolated in a decomposition analysis, as demonstrated in section 6.1 of this paper.

5.2 **Energy prices**

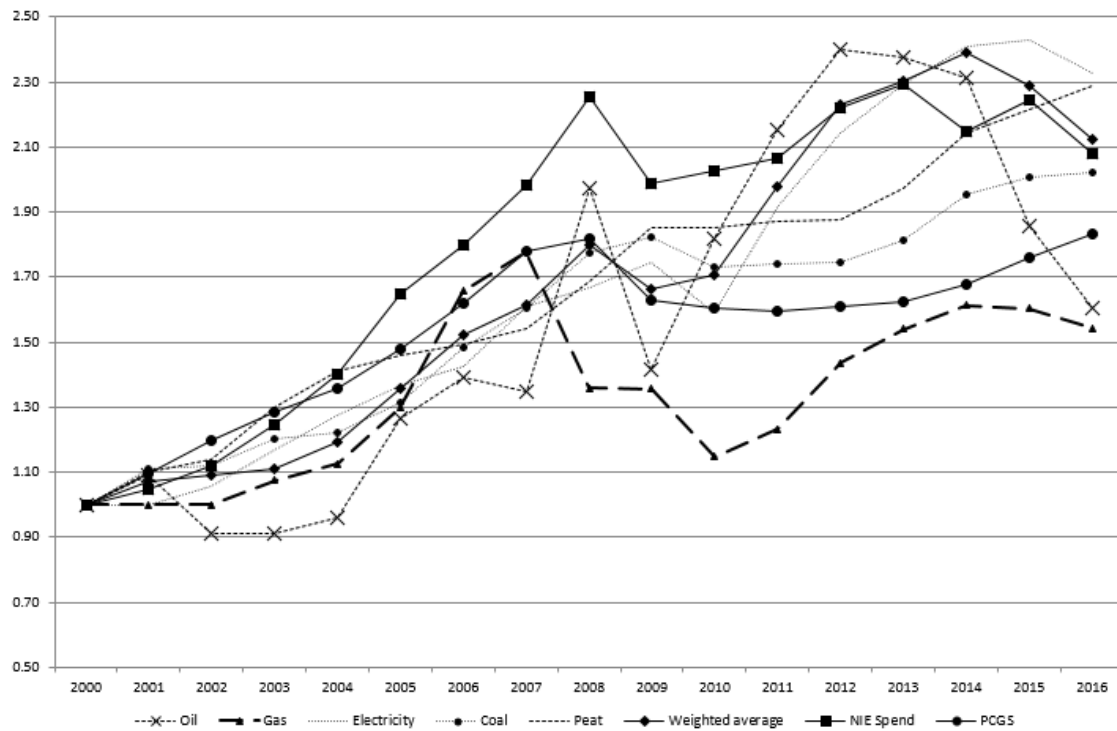
256 Residential energy prices are collected and published by SEAI in a historical time series¹⁶ (SEAI, 2018c). Indexed
257 residential energy prices for individual fuels, as well as an overall average price weighted by the share of each
258 fuel in annual residential energy consumption, are presented in Figure 1. Also included are national income and
259 expenditure energy spend (NIE) and personal consumption of goods and services (PCGS), both of which are
260 discussed in section 5.3.

¹⁴ The question of using seasonal heating degree days rather than annual was raised in the 2018 SEAI Energy in the Residential Sector report (SEAI, 2018a) but is considered beyond the scope of this paper.

¹⁵ See SEAI publication Energy in the Residential Sector 2018 section 3.5 figure 35 (SEAI, 2018a)

¹⁶ The residential Fuel Costs Comparison data set includes consumer prices and includes all taxes that consumers pay including VAT and the carbon tax. A Carbon Tax was introduced for Oil, L.P.G and Natural Gas on 1st May 2010. Initially set at 15 euro per tonne in 2010 but increased to 20 euro per tonne in 2012. The Carbon Tax was extended to Coal and Peat on 1 May 2013 and increase on 1 May 2014.

Figure 1 Index of Irish residential energy prices (2000=1)



Data sources: SEAI, 2018a, CSO, 2017e&f.

261 Over the period 2000 – 2016 energy prices rose for all fuels. Interestingly, natural gas and oil prices, the two most
 262 dominant residential space-heating fuels, displayed price decreases for a number of years after peaks in 2007,
 263 which coincides with the onset of the economic recession. So when the recession hit, most households did not
 264 have higher energy prices to contend initially.

5.3 Central Statistics Office Survey Data

265 The Central Statistics office (CSO) also annually calculates energy spend for national income and expenditure
 266 (NIE) tables (CSO, 2017i). The NIE energy spend is categorised as fuel and power excluding motor fuel. NIE is
 267 also included in Figure 1, measured in current prices, and displays a similar pattern to the estimated
 268 weighted-average price based on the fuel cost comparison and energy balance data. Fuel and power prices rose
 269 faster than personal consumption of goods and services (PCGS) over the period examined (CSO, 2017j).
 270 Disposable income, defined as gross income less direct taxation, is produced as part of the annual national
 271 accounts by the CSO (2017a) and is included in the decomposition analysis in this paper.

5.4 Summary of data sources and assumptions

272 A summary of the data inputs and assumptions used for the LMDI-I decomposition analysis in this paper is
273 presented in Table 1.

274 Table 1 Summary of data sources for LMDI-I decomposition analysis of Irish residential space heating

Variable	Source	Description
Disposable income	CSO (2017a)	Official government statistics from annual national accounts.
Energy spend	CSO (2017e)	Official government statistics from national income and expenditure tables.
Population	CSO (2017c)	Official government statistics from 5-yearly census and interpolation for interim years
Dwellings	CSO (2017b)	Official government statistics from census and household budget surveys.
Floor Area	Adapted by SEAI from CSO (2017d)	Estimated by SEAI based on planning permission applications.
Space heating energy consumption	adapted from SEAI (2018a)	Adapted from SEAI energy balances as described in section 5.1.1
Technology efficiencies	authors' estimates	See details in appendix 2.
Useful energy (Exergy)	authors' estimates	Based on space-heating energy consumption estimates combined with technology efficiency assumptions.

6 Results

275 The residential sector space-heating energy demand in Ireland is examined using three different methodologies to
276 answer the question of whether the economic recession or the Government energy-efficiency retrofit programme
277 was the cause of a fall in residential space-heating energy consumption between 2007 and 2012.

278 Firstly, the results of an 8-factor LMDI-I decomposition analysis for Irish residential space-heating demand, using
279 Equation 2, are analysed to interpret the underlying drivers in section 6.1. Secondly, in section 6.2,
280 energy-efficiency savings, quantified from the top-down LMDI-I decomposition analysis, are compared to the
281 retrofit programme bottom-up residential sector savings as estimated in the NEEAPs. Finally, counterfactual
282 scenarios, where the bottom-up energy-efficiency retrofit savings are added to historical actual energy demand to

283 represent hypothetical scenarios of what trends would have looked like without those policy interventions, are
284 examined in section 6.3.

6.1 Top-down LMDI-I decomposition analysis

285 Figure 2 provides a summary of the LMDI-I analysis for three different time periods. It can be seen that increasing
286 population growth resulted in more energy demand throughout the 16-year period. The most significant impact
287 for population occurred between 2000 and 2007. The trends in average floor area display a similar trend, with
288 strong growth between 2000-2007 resulting in increased energy demand, but a slowdown or plateau in the change
289 in floor area post 2007. A fall in occupancy over the period resulted in an increase in energy demand from 2000
290 to 2014, but there appears to be a reversal of the trend in the latter phase of the period examined. Predictably,
291 technology improvements result in steady energy-efficiency savings throughout the period.

292 Over most of the 16-year period examined, the impact of fuel switching is towards fuels that are converted more
293 efficiently, which results in less energy consumption and persistent energy savings. However, between 2008 and
294 2013 there appeared to be a reversal in the fuel switching metric impact, which coincides with a shift back towards
295 solid fuels (coal and peat). Such a trend is likely to have been driven by a shift from primary-heating to secondary-
296 heating sources, rather than a change to the primary-heating source. In times of economic hardship the use of
297 secondary heating can help to save on monthly and annual fuel bills.

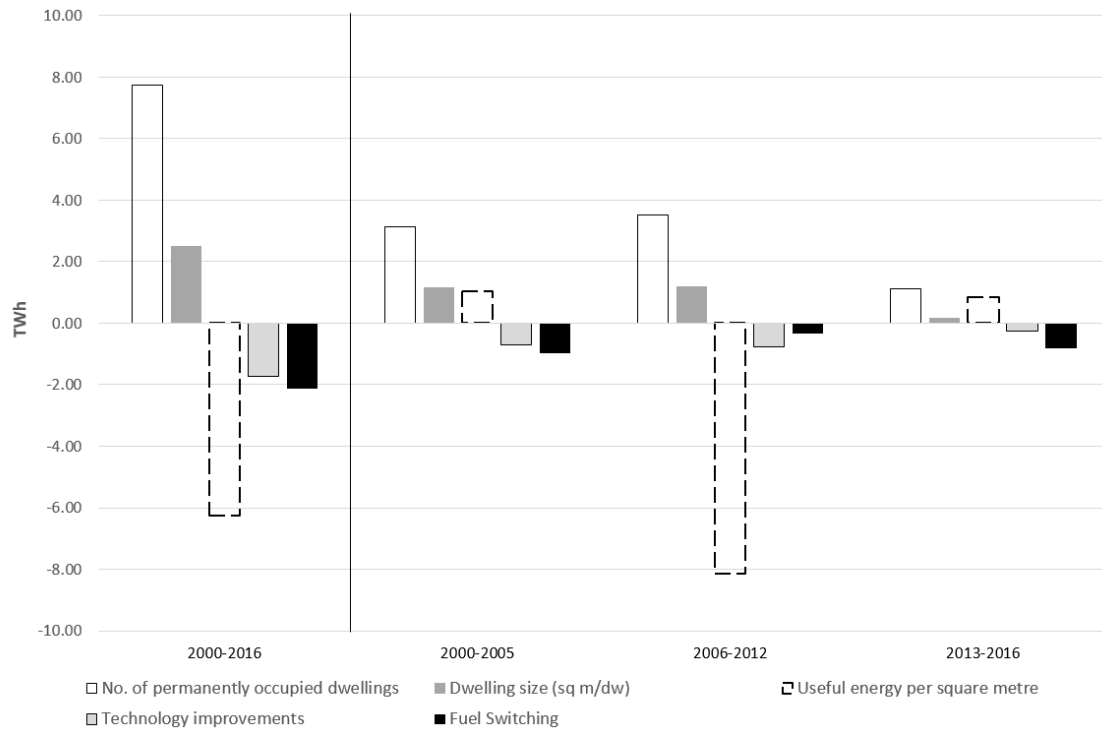
298 The energy savings from the improvements to useful energy per square metre, the technology efficiency
299 improvements, and fuel switching over the 16-year period all counteract the increased energy demand from more
300 dwellings, increasing floor area per dwelling, and decreasing occupancy rates. The useful energy per square metre
301 metric displays an initial deterioration between 2000 and 2002. There was a gradual improvement between 2002
302 and 2005, but only small savings were realised. However, between 2007 and 2012 there appears to be a significant
303 increase in the savings associated with the useful energy per square metre metric.

304 Of significance however is the definitive change in 2014, when energy savings were no longer recorded from the
305 useful energy efficiency per square metre metric, a time that corresponds with the return of strong growth in the
306 Irish economy. As energy-efficiency retrofit improvements (such as insulation of the building envelope) should
307 not be reversible, the trend post 2014 points towards a reversal of behavioural trends adopted during the economic
308 recession.

309 The factors of disposable income per dwelling (combining the 2nd-4th terms in Equation 2) and disposable income
310 per person (combining the 2nd and 3rd terms in Equation 2) provide evidence of a strong influence of the economic
311 recession, with savings only recorded in the period 2008-2011 (note that as a reciprocal term, the interpretation is

312 the inverse of the results). This is corroborated in Figure 2, where net useful energy per square metre savings are
 313 only recorded for the period 2006 to 2012.

Figure 2 Summary of LMDI-I decomposition analysis on Irish residential space heating



Source: Results are based on authors' calculations using data sources: SEAI, 2018a, CSO, 2017a,e&f.

Note: A negative value in Figure 2 signifies an energy savings. While none of the factors pass the monotonicity axiom for the periods examined, the relative size of the savings of the different factor give a reasonable picture of their influence.

6.2 Top-down V bottom-up quantification of savings

314 Table 2 compares the cumulative additive technology and useful energy per square metre savings from the LMDI-
 315 I top-down decomposition analysis in section 6.1 directly to the NEEAP savings estimated from the residential
 316 retrofit improvements, the building regulations Part-L revisions and boiler efficiency regulation.

317 Table 2 **Estimated absolute energy efficiency savings related to Irish residential space-heating**

GWh	2006 to 2016	2006 -2012
	LMDI-I Technology Improvement	1,031
LMDI-I Useful energy per square metre (incl. building envelope improvements & behaviour)	7,300	8,127
Bottom up NEEAP savings including Building regulations and Retrofit improvements	4,443	2,256

Results for LMDI-I analysis are based on authors' calculations using data sources: SEAI, 2018d, CSO, 2017a,e&f, DCCAE 2017b, DCENR 2010, 2012, 2015.

Note: The results included in Table 2 estimate that technology efficiency resulted in consistent energy savings over the period 2006 to 2016. This is an example of monotonic energy efficiency improvements and so the annual savings can be cumulated for the period 2000-2016. As the useful energy per square metre was not monotonic throughout the period 2000-2016 the annual savings cannot be cumulated for the entire period but rather only from 2006-2012.

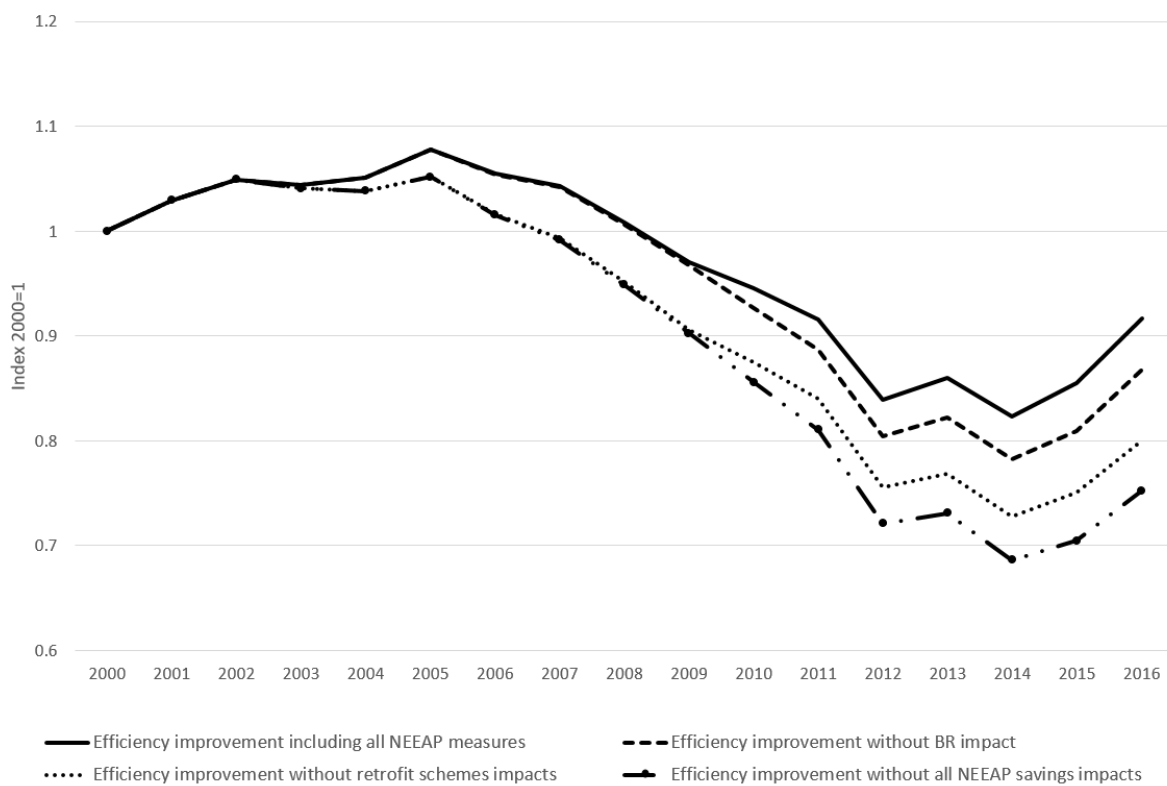
318 The top-down efficiency savings calculated from the LMDI-I decomposition analysis (7,300 GWh from 2006 -
 319 2016) are significantly higher than the energy-efficiency savings estimates in NEEAP 4 achieved by the end of
 320 2016 for residential space heating only savings¹⁷ (4,443 GWh final energy) over the period 2006 to 2016 (DCCAE,
 321 2017b). However, the best period to compare is from 2006-2012, as the useful energy per square metre savings
 322 from the LMDI-I analysis in section 6.1 were monotonic in that period and so can be readily accumulated. The
 323 results in the left-most column of Table 2 show the top-down LMDI-I useful energy per square metre savings
 324 (8,127 GWh) were significantly higher than the bottom-up NEEAP savings (2,256 GWh). When the technology
 325 efficiency and useful energy per square metre improvements (i.e. building envelope) are combined, the top-down
 326 LMDI-I efficiency savings were 3.9 times greater than the bottom-up NEEAP savings. Table 2 includes additional
 327 evidence to that provided by the LMDI-I analysis in section 6.1 that the recession rather than the energy-efficiency
 328 retrofitting schemes are driving the overall energy trends.

¹⁷ Column 4 of Table 9 in NEEAP 4 excluding the savings from the building regulations related to non-residential buildings, the greener homes scheme and the residential lighting (DCCAE, 2017b). Data for NEEAP tables were revised in 2018 by SEAI, revised data are included in the analysis in this paper.

6.3 Testing the hypothesis that the improvement is due to retrofitting

329 Counterfactual scenarios were calculated by adding the bottom-up NEEAP energy-efficiency savings to the actual
 330 historical residential space-heating energy consumption. That hypothetical demand was then decomposed in a
 331 similar manner to the actual historical demand as described in section 6.1. The resulting useful energy per square
 332 metre improvement estimates are compared to the results based on actual demand, effectively facilitating a
 333 comparison with and without the BRs and retrofit savings, as shown in Figure 3.

Figure 3 Pattern of Irish residential space-heating efficiency progress with and without the BR or grants savings



Source: Results are based on authors' calculations using data sources: SEAI, 2018d, CSO, 2017a,e&f, DCCA 2017b, DCENR 2010, 2012, 2015.

334 Over the period that the 2002 BRs were in place, overall space-heating demand grew driven by the strong growth
 335 in building activity, net immigration and the growth in the economy and dwelling size. The number of new houses
 336 built between 2003 and 2008 represented over a quarter of all residential permanently occupied dwellings in 2016
 337 (CSO, 2017b). As the useful energy per square metre peaked in 2005, it appears that the BRs can at least partially
 338 explain the change in direction of efficiency post 2005.

339 The efficiency index trend of the counterfactual scenario without the impact of the BRs displays a peak in the
340 deterioration of the energy-efficiency improvement in 2007. This suggests that the impact of the 2002 BRs is
341 responsible for the difference between the efficiency index improvement from 2003 to 2007 and that of the index
342 that excluded the savings from the BRs.

343 As the trend in the BRs scenario between 2007 and 2012 is less severe than the index for the actual change in the
344 useful energy-efficiency index, the BRs are likely to be responsible for continued exergy-efficiency improvements
345 post 2007 and so partially responsible for the steep fall in the useful energy-efficiency metric between 2007 and
346 2012. The impact of those BRs and the 2011 BRs revision are relatively small, most likely because of the sharp
347 contraction in the building sector which coincided with the introduction of the 2008 BRs.

348 It can also be established from Figure 3, that in the counterfactual scenario where only the retrofit savings were
349 added to the demand, the impact of the retrofit grants scheme savings appears to be small (a cumulative difference
350 of 6.4% compared to actual ex-post exergy-efficiency index in 2016). The counterfactual scenarios still displaying
351 a sharp fall in efficiency between 2007 and 2012 provide the strongest quantitative evidence that it was the impact
352 of the economic recession and not the national retrofit schemes that drove the efficiency improvement between
353 2007 and 2012.

7 Discussion

354 The approach of including macroeconomic variables in a decomposition analysis described in this paper facilitates
355 a greater understanding of factors influencing space-heating energy demand. The introduction of exergy analysis
356 assists in isolating the impact of technology efficiency and fuel switching from measures such as efficiency
357 improvements to the building envelope, improvements which are often achieved through building regulations or
358 energy-efficiency programmes. The approach addresses the problem of conflated energy-efficiency estimates
359 from a number of factors (technology changes, fuel switching and exergy efficiency) resulting in overestimates
360 of the potential for energy-efficiency improvements and the most effective policy pathways to achieve efficiency
361 improvement remaining opaque and intangible.

362 The analysis found that the economic recession was responsible for most of the fall in space-heating demand
363 rather than a national energy-efficiency retrofit programme. The CSO also has interesting qualitative survey data
364 relating to energy that provides evidence that the economic recession could be responsible for the sharp drop in
365 energy demand between 2008 and 2012. From July to September 2012 (Q3) a module on the effect on households
366 of the economic recession was included in the Quarterly National Household Survey (QNHS) (CSO, 2013). The
367 questionnaire referred to the twelve months prior to that time period. There was not an explicit reference to energy

368 spend or consumption, but some of the questions asked related to utilities. Households which responded as
369 experiencing difficulty in managing bills and debts during the 12 months prior to the date of interview determined
370 that it was primarily due to higher than expected or additional costs (73%) or loss of income (47%). The majority
371 (90%) of households experiencing financial difficulty cited higher or additional utility bills as one of the reasons
372 they experienced financial difficulty.

373 More recently, the 2016 Household Budget Survey (HBS) results suggest that in 2015 households spent more on
374 average on energy than in the 2009/2010 survey (CSO, 2016). Prima facie, this reflects the influence of higher
375 energy prices, however, the comparison to 2010 could also be distorted by people actively trying to cut back on
376 energy bills during the economic recession.

377 In the analysis in this paper broad assumptions about technology improvements are adopted. To improve this
378 analysis and further develop energy balances, more technology tracking is needed at the level of national and
379 international energy statistics. Specifically data on boiler replacement rates would be very useful and potentially
380 facilitate the use of top-down methodologies to quantify NEEAP savings. The advantage of such an approach
381 would be that rebound and other behavioural trends could be accounted for in the NEEAP savings.

382 It would be instructive to get to the root of the reasons behind the fall in space heating demand once the economic
383 recession took hold in 2008. Ideally this information could be used to instigate energy-efficient behaviour but
384 without the economic hardship. Data such as internal temperatures, changes in internal temperatures over time,
385 the impact of changing occupancy levels and especially daytime occupancy are needed for such analysis and are
386 currently unavailable for the Irish residential sector. Perhaps, with the rise in energy monitoring devices and apps
387 which can control space heating parameters this information may become available in the future.

388 One of the impacts that may not be captured in official national energy statistics is non-traded fuels, which consists
389 mostly of wood but could also include some sod peat consumption. While official energy balance statistics point
390 towards increased secondary fuel use, data on the installation of solid fuels stoves and the fuel use for these
391 technologies are not available.

392 The question of the extent of fuel switching to solid fuels (coal, peat and wood) in homes with oil central heating
393 at times of high oil prices and or economic hardship also requires further data and investigation. The general
394 perception is that solid fuels are cheap, but as they are used in less efficient technologies (open fires or stoves) the
395 actual price paid in kilowatt hour (kWh) of heat is often more than it would be if that heat was produced from an

396 oil or natural gas central heating boiler¹⁸. Education or information campaigns could help to change usage patterns
397 of secondary fuels based on value for money and improving air quality within homes.

8 Summary and Conclusions

398 The decomposition analysis included in this paper elucidates that changes in energy consumption, disposable
399 income and energy price effects, rather than national energy efficiency retrofit programmes, were the main drivers
400 of space heating trends over the period examined. Savings were realised from energy-efficiency retrofit
401 programmes over the period as recorded in the National Energy Efficiency Action Plans. However, to date only
402 approximately 23% of the housing stock has received retrofit grant aid (SEAI, 2018d). Even taking into account
403 rebound effects, savings from technology and building envelope improvements should be predominately
404 irreversible. The significant fall in useful space-heating energy demand per metre squared between 2007 and 2012,
405 as well as a reversal of the trend from 2014, which mirrors macroeconomic trends, points towards the dominance
406 of behavioural changes linked to the macroeconomic environment rather than energy-efficiency savings from
407 retrofit schemes.

408 In addition, the absolute energy-efficiency savings measured using the top-down decomposition methodology
409 were 3.5 times greater than those recorded for the NEEAP using bottom-up methods which includes the impacts
410 of energy-efficiency retrofit schemes and building regulations. An advantage of a top-down ex-post analysis is
411 that it records the actual energy consumption after any energy efficiency savings have been realised, and thus
412 includes the behavioural and rebound effects which are not easily measured using bottom up techniques.

413 Counterfactual scenarios without bottom-up NEEAP savings (building regulation and energy efficiency retrofit
414 grant schemes), display the same trend in exergy efficiency as when those NEEAP savings are included. The sharp
415 drop between 2007 and 2012 displayed in all scenarios indicates that behavioural changes due to the
416 macroeconomic environment were driving the space-heating energy demand trends.

417 The analysis in this paper highlights that while energy-efficiency policy interventions are working, further
418 resilience to a fall in disposable income and energy price fluctuations needs to be achieved to ensure continuing
419 reductions in energy consumption for space heating. While the analysis was specific to Ireland it is likely that
420 similar trends are observed elsewhere with a similar space-heating dependency, indicating that the methodologies

¹⁸ For example in the latest SEAI domestic fuel cost comparison (January 2018) coal used in a stove with an efficiency of 60% costs 9.6 cents per kWh, whereas oil used in a boiler with an efficiency of 80% costs 9.2 cents per kWh (SEAI, 2018c). As solid fuels are most often used for heating individual rooms rather than the entire houses there is also a difference in the level of energy service provided.

421 used and policy suggestions proposed, could be widely considered. The results of the analysis point to a need for
422 more detailed cost benefit analysis and considered appraisal of where the funds of the cost of retrofit programmes
423 should originate.

424 Increased building regulation stringency will limit the demand of the future building stock, however there needs
425 to be monitoring and enforcement to ensure compliance. For the existing residential building stock, a much wider
426 and deeper roll out of the national retrofit program is an imperative in order to reduce energy consumption and
427 associated emissions and particulates from the residential sector.

428 However, given the conclusion that the economic recession had a significant influence on the trend the real policy
429 challenge is to bring about some of the behavioural changes that led to less energy consumption during the
430 recession but without the economic hardship. Further analysis is require to isolate the underlying behavioural
431 changes and engage and influence consumers.

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Appendix 1: Bottom up Energy-Efficiency savings

432 A time series of the bottom up residential energy efficiency savings estimates is included in Table A1.1. which
 433 includes savings from 2000, the savings exceed NEEAP savings which are from policies introduced from 2007,
 434 as in limited circumstances earlier policies that generate additional savings in the period 2007-2016.

Table A1.1 Irish NEEAP bottom-up energy-efficiency savings estimates

GWh PEE cumulative	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
All NEEAP savings	3	3	3	60	247	510	828	1098	1284	1525	2064	2488	2792	3048	3380	3689	4028
All NEEAP savings - electricity	0	0	0	0	0	0	2	3	5	7	27	40	47	51	58	63	66
All NEEAP savings - natural gas	1	1	1	24	99	204	332	440	515	611	810	966	1080	1179	1305	1423	1556
All NEEAP savings - oil	2	2	2	35	148	305	494	654	763	903	1188	1416	1584	1731	1916	2091	2288
All NEEAP savings - solid fuels	0	0	0	0	0	0	0	1	1	3	39	66	80	87	101	111	118
BRs and boiler efficiency	0	0	0	56	243	506	809	1062	1230	1433	1598	1760	1919	2105	2300	2504	2778
BRs and boiler efficiency - electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BRs and boiler efficiency - natural gas	0	0	0	22	97	202	324	425	492	573	639	704	767	842	920	1002	1111
BRs and boiler efficiency - oil	0	0	0	33	146	303	485	637	738	860	959	1056	1151	1263	1380	1503	1667
BRs and boiler efficiency - solid fuels	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Grant schemes	3	3	3	4	4	4	19	36	54	91	466	728	873	942	1080	1185	1250
Grant schemes - electricity	0	0	0	0	0	0	2	3	5	7	27	40	47	51	58	63	66
Grant schemes - natural gas	1	1	1	1	1	1	8	15	23	38	170	262	313	337	385	422	445
Grant schemes - oil	2	2	2	2	2	2	9	17	25	43	230	361	433	468	536	589	621
Grant schemes - solid fuels	0	0	0	0	0	0	0	1	1	3	39	66	80	87	101	111	118

Sources: Compiled from estimates by DCENR (2010, 2013 & 2015) and DCCAE (2017a&b).

435 In the first Nation Energy Efficiency Action Plan (NEEAP) published in 2010, 44% of the total savings (32,195
436 GWh PEE) came from the residential sector (DCENR, 2010). In the second plan the buildings share (residential
437 and commercial sector) accounted for 45% of the total savings (DCENR, 2012). In the third plan, published in
438 2014 (DCENR, 2015), the buildings share fell to 32% of total savings and in the fourth plan buildings accounted
439 for just under 39% of the total 2016 final energy savings (DCCAE, 2017b). Other European countries also rely
440 on savings from the residential sector in their NEEAPs, typically it is the largest source of savings accounting for
441 30%-50% of the total savings (Dineen and Ó Gallachóir, 2011).

442 Reasons for the drop in the share of the contribution from the residential sector and buildings include revisions to
443 the number of residential building projections and grant uptake, which were revised downwards once the impact
444 of the economic recession became more apparent. There were also revisions to historical savings based on
445 methodological refinements and the availability of some ex-post data. A detailed discussion on the revision of the
446 NEEAP savings methodology is available in (Dineen and Ó Gallachóir, 2017).

Appendix 2: Technology efficiency calculations

447 The starting point for the technology energy efficiency data in table 5.5 was the UK Standard Assessment
 448 Procedure (SAP) energy rating system for boiler efficiency from 1997 (BRE, 2001).

Table A2.1 SAP residential heating technology efficiencies

Boiler or heater type	Seasonal Efficiency (%)
Decorative fuel-effect gas fire, open to chimney	20
Open fire in grate (no back boiler)	32
Open fire with back boiler to radiators:	55
Closed solid fuel fire with back boiler to radiators (in heated space):	60
Oil boiler, standard, pre-1985	65
Oil boiler, 1985-97	70
Oil boiler, 1998 or later	79
Condensing oil boiler	83
Gas boiler, pre-1998, with fan-assisted flue	68
Gas boiler (incl. LPG), 1998 or later, with permanent pilot light	69
Gas boiler (including LPG), 1998 or later, non-condensing, auto ignition	73
Gas boiler, 1998 or later, condensing, automatic ignition	83
Electric storage heaters (at point of use)	100

Source: BRE, 2001.

449 The equipment efficiency was combined with assumptions about the rate of replace of old boilers and the
 450 efficiency of the newly installed boilers (in new and existing homes) to build a model time series of the overall
 451 boiler stock efficiency improvements. The assumptions used are summarised in table 3.

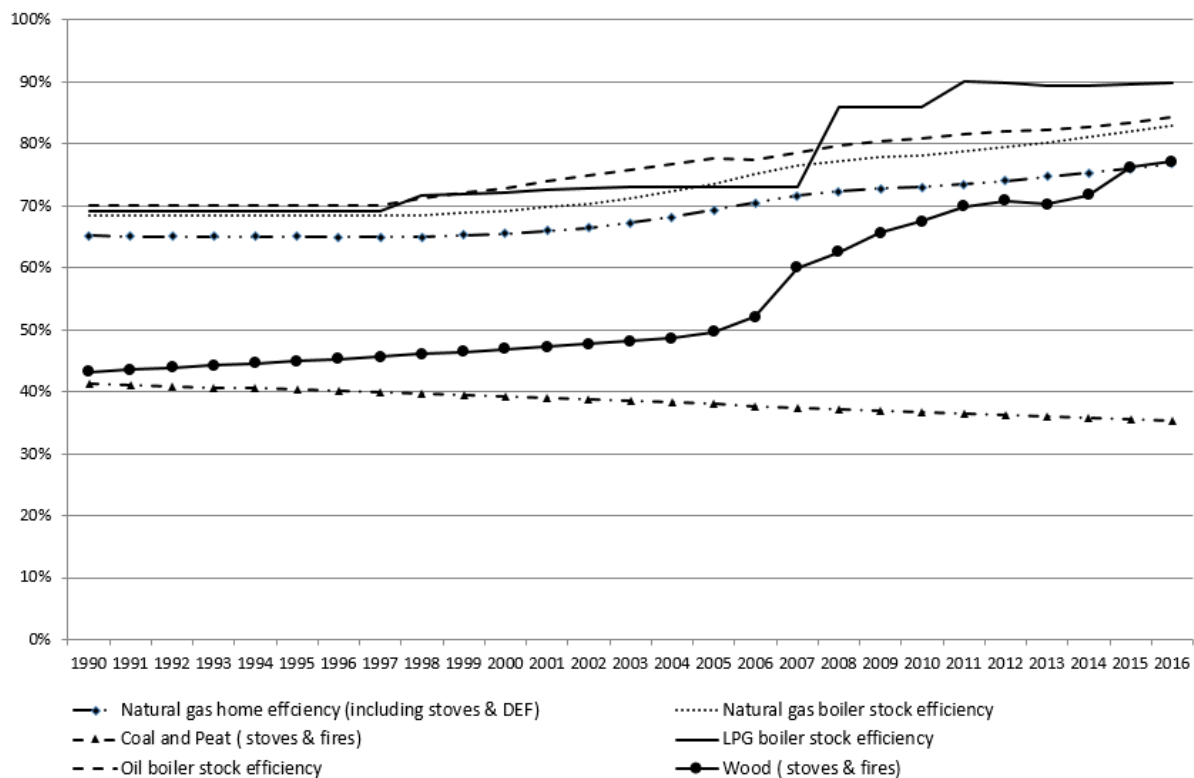
Table A2.2 Assumptions for Irish space-heating technology efficiency conversion factors

Boiler replacement rate pre-1995 (1 in 25 years)	4%
Boiler replacement rate 1996 - 2000 (1 in 20 years)	5%
Boiler replacement rate 2000 - 2007 (1 in 15 years)	7%
Boiler replacement rate post-2007	4%
Share of condensing boilers in oil-fired homes from 1990 -1997	5%
Share of condensing boilers in oil-fired homes from 1998 -2007	10%
Share of condensing boilers in oil-fired homes from 2008 -2010	15%
Share of condensing boilers in oil-fired homes from 2008 -2012	50%
Share of condensing boilers in oil-fired homes from 2013	100%
Share of usage of decorative effect fires in natural gas homes	6.60%
Share of usage of stoves or closed gas fires in natural gas homes in 1990	2.20%
Share of usage of stoves or closed gas fires in natural gas homes in 2016	8.80%
Share of open fires with back boilers in 1990	39%
Share of open fires with back boilers in 2016	13%
Share of closed fires or stoves with back boilers	20%
Share of closed fires or stoves with back boilers	46%

Source: Authors' assumptions.

452 Figure 4 shows the progress over time in technology efficiency by fuel. It is interesting to note that although
453 natural gas boilers have a very similar efficiency to oil boilers, overall energy conversion in natural gas homes
454 appears less than oil homes. Given that natural gas homes use decorative effect fires, open fires or stoves for the
455 purpose of space heating, when these less efficient technology usages is considered the gas conversion efficiency
456 drops relative to gas boiler efficiency only. Of course, homes that use oil boilers are also likely to have and use
457 open fires or stoves, however the overwhelming majority will use solid fuels for those less-efficient secondary-
458 heating technologies.

Figure 4 Irish space-heating technology efficiency trends over time



Source: Authors' calculations.

459 To sense check the estimates for this paper, the oil and gas boiler efficiencies derived from the assumptions in
 460 Table A2.1 where compared to the BER database. The results were almost identical to the BER database, which
 461 quantifies the housing stock oil boiler efficiency at 84.2% and natural gas boiler efficiency at 82% for the database
 462 accessed in February 2018 (SEAI, 2018b).

463 The trend for coal and peat efficiency of conversion, which initially may appear to be counter-intuitive can be
 464 explained by large shift from solid fuel based heating prevalent in the early 1990's to central heating. With the
 465 shift to central heating the use of back boilers falls as open fires or stoves became secondary rather than primary
 466 heating sources and the efficiency of open fires fell in proportion to the drop in back boilers.

467 While there is evidence of strong growth of solid fuel stoves, it is assumed that these stoves are more likely to be
 468 fuelled by wood and so there is not a reversal in trend for coal and peat conversion linked to the rise of solid fuel
 469 stoves.

470 The wood and wood waste trend initially appears very similar to that of coal and peat, however with the addition
 471 of recent modern wood fuels such as wood pellets, chips and briquettes, the efficiency of conversion for wood
 472 increased significantly in recent years.

473 Direct electric heating and heat pumps are recorded separately in the energy balances. The efficiency of electricity
 474 use for space heating is assumed to be 100% efficient at the point of use. For the renewable heat portion of heat
 475 pumps (ambient energy or sometimes referred to as geothermal energy), a coefficient of performance (COP) is
 476 assumed, as presented in Table A2.2. With the rise in the share of air source pumps the COP of the stock of heat
 477 pumps has been falling in recent years.

Table A2.3 Time series of Irish seasonal efficiency of residential heat pump technologies

	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
COP	3.5	3.4	3.4	3.4	3.4	3.3	3.3	3.2	3.0	2.9	3.0	2.9	2.9	2.8	2.7

Source: Estimated from European Heat Pump association (EHPA, 2014)

Appendix 3: LMDI-I decomposition analysis equations

478 The following Log Mean Divisia Index I (LMDI-I) decomposition analysis equations are used in the
479 analysis in this paper. The multiplicative (ratio [R] or product) form of LMDI-I, is defined as follows:

Equation A3.1

$$R_i^t = \exp \sum_i \left[\frac{L(E_i^T, E_i^0)}{L(E^T, E^0)} \ln \left[\frac{X_i^T}{X_i^0} \right] \right]$$

480 Where $R = E^T / E^0$. E^T is the total energy consumption in year T. E^0 is the total energy consumption in year 0 and
481 i denotes the sub-sector. X represents a factor of an identity equation being decomposed. The function L is the log
482 mean average as described by equation A3.2.

Equation A3.2

$$L(a, b) = \frac{a - b}{\ln(a) - \ln(b)}$$

483 With $a, b > 0$ and $a \neq b$; $\ln =$ natural log, $\exp =$ exponential. The result of a multiplicative analysis (R_i^t) is a
484 percentage change, where a value of less than 1 represents less overall energy consumption and thus an energy-
485 efficiency improvement.

486 The additive (or absolute) LMDI-I term is given by equation A3.3:

Equation A3.3

$$E_i^t = \sum_i L(E_i^T, E_i^0) \ln \left[\frac{X_i^T}{X_i^0} \right]$$

487 Where E_i^t is the change in energy consumption between year T and year 0, and is measured in absolute energy, i
488 and X are similarly as defined for Equation 1. The only difference is the weighting term which is an absolute
489 number in the additive equation rather than a share or percentage term in the multiplicative equation.