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Author(s)	Dennehy, Emer R.; Dineen, Denis; Rogan, Fionn; Ó Gallachóir, Brian P.
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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

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

1 Introduction

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

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

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

2 Literature review

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

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

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

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

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

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

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[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.

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

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

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

3 Policy context

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

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

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

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

4 Methodology

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

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[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).

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

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

Equation 1

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

An advantage of the proposed breakdown (by fuel[7] and also including technology efficiencies) is that the analysis becomes a closer approximation to that of technology and engineering modelling in terms of the datasets and assumptions included. It also facilitates identifying the impacts of readily-available policy levers such as technology-efficiency standards and the incentivisation of certain technologies (e.g. encouraging fuel switching). Another advantage is that the efficiency metric, when based on useful energy, approximates the theoretical concept of exergy.

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

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[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.

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

Equation 2

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

Where E is the total energy used for space heating. D is disposable income, S is energy spend on space heat, P is the total population, Dw is the total of permanently occupied dwellings, F representing the floor area in square metres[8]. *Eu* is useful energy (proxy for exergy) and i relates to the different fuels or energy sources that make up total residential energy consumption.

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

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

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

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[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.

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

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

The useful energy-efficiency improvement term (a proxy for exergy efficiency) includes the impact of the building envelope changes, as well as behavioural and rebound effects that cannot readily be measured explicitly. As reliable floor area by fuel type is not available in national energy statistics, and because a lot of dwellings will use different fuels for primary and secondary heating, the useful energy per square metre term is not analysed by fuel. 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 of this paper the term fuel switching should be interpreted as the aggregate impact of decisions by individual homeowners to switch their main source of heating fuels. Rural dwellings in Ireland and older dwellings in urban areas are more likely to rely on oil central heating, as the gas grid does not reach those areas. This is particularly relevant in the context of fuel switching as changes to fuel shares are more likely to signify a shift from a primary heating source to a secondary or supplementary heating source, with the secondary-heating source usually being a solid fuel based open fire or stove. As supplementary electricity heating cannot be isolated from other appliance usage it is not included in the analysis. The technology efficiency calculations are based on the first law of thermodynamics and are explained in detail in Appendix 2.

In order to attribute changes in energy or emissions a decomposition analysis is often employed to understand the underlying factors driving the overall energy consumption or emission trends. Equation 2 can be used as the basis (identity equation[11]) of a decomposition analysis, to understand the influence of the chosen factors on space-heating energy demand. There are two broad categories of decomposition analysis, namely; index decomposition analysis (IDA) and structural decomposition analysis (SDA). IDA is limited to factors directly included in identity equations, whereas SDA can investigate factors indirectly related to consumption. However, as SDA can only be applied to sectors of the economy for which input output tables are available. Therefore, only IDA is appropriate for analysis of the residential sector.

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

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[11] An equation describing energy consumption by different constituents is termed and identity equation.

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

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

The NEEAP savings are quantified based on bottom-up engineering estimates by the Sustainable Energy Authority of Ireland (SEAI), the grant scheme administrator.[12] Statistics on the number of households upgraded and energy-efficiency measures installed under the grant scheme are used to calculate the energy and CO_2 savings. The estimated savings are based on assumed efficiency improvements resulting from the installation of approved building fabric and heating system-upgrades in existing dwellings. Savings per-measure and per-dwelling-type are calculated using the DEAP software tool. Final energy savings per dwelling are based on modelled demand reduction from installed measures (actual) since programme inception. Estimates of the BR savings are calculated using statistical information from BER database for existing dwellings to derive the percentage of dwellings with oil or gas boilers that will be replaced by more efficient boilers. Assumptions are made about the boiler lifespan in the absence of boiler installation numbers.

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

5 Data availability

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

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

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

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

5.1 **Energy demand data**

5.1.1 Share of fuels used for space heating

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

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

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

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[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

Weather correction is applied to all space-heating consumption to account for year-to-year changes that can significantly impact on demand. Weather (in particular outdoor temperature) has a strong impact on household heating energy. A warm year can result in energy demand reductions not due to energy efficiency, but rather to weather changes. In order to distinguish between energy-demand changes due to weather from other factors (recession, retrofit, etc.) weather correction is applied to the data. SEAI currently apply a population-weighted degree-days methodology for weather correction on an annual basis and that is also the approach adopted in this paper[14]. A known consequence of weather correction methodology is to overestimate consumption in mild years and underestimate consumption in cold years[15].

5.1.3 Technology efficiencies

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

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

5.2 **Energy prices**

Residential energy prices are collected and published by SEAI in a historical time series[16] (SEAI, 2018c). Indexed residential energy prices for individual fuels, as well as an overall average price weighted by the share of each fuel in annual residential energy consumption, are presented in Figure 1. Also included are national income and expenditure energy spend (NIE) and personal consumption of goods and services (PCGS), both of which are discussed in section 5.3.

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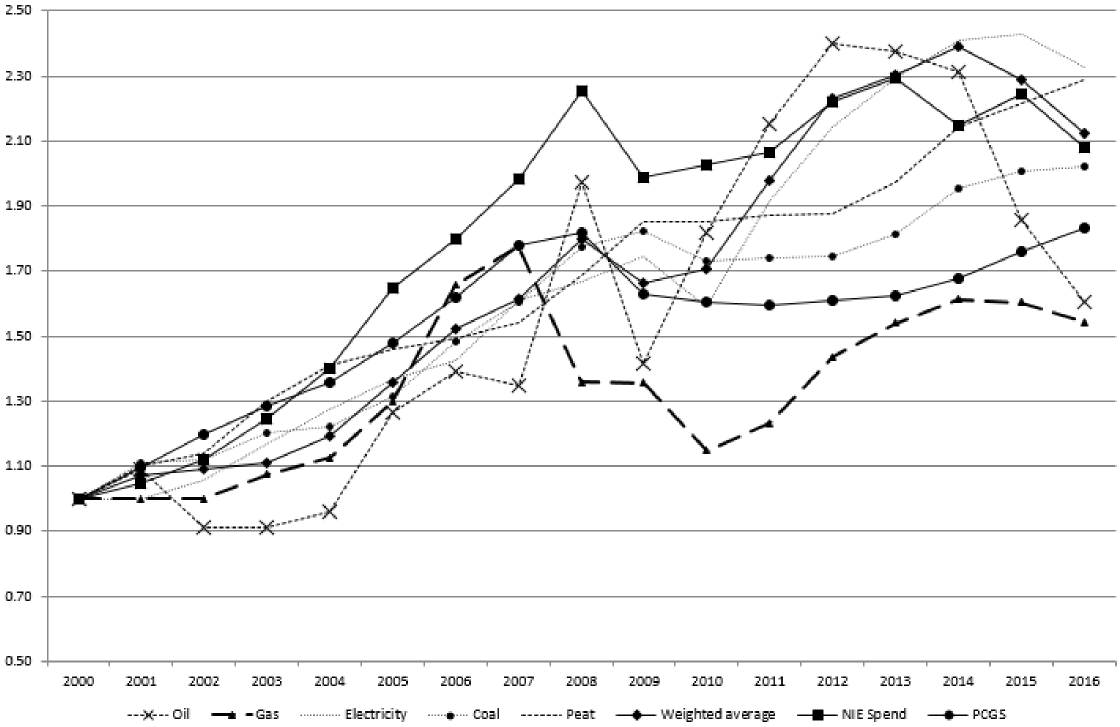
[14] The question of using seasonal heating degree days rather than annual was raised in the 2018 SEAI Energy in the Residential Sector report (SEAI, 2018a) but is considered beyond the scope of this paper.

[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.

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

5.3 Central Statistics Office Survey Data

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

5.4 Summary of data sources and assumptions

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

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

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

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

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

6.1 Top-down LMDI-I decomposition analysis

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

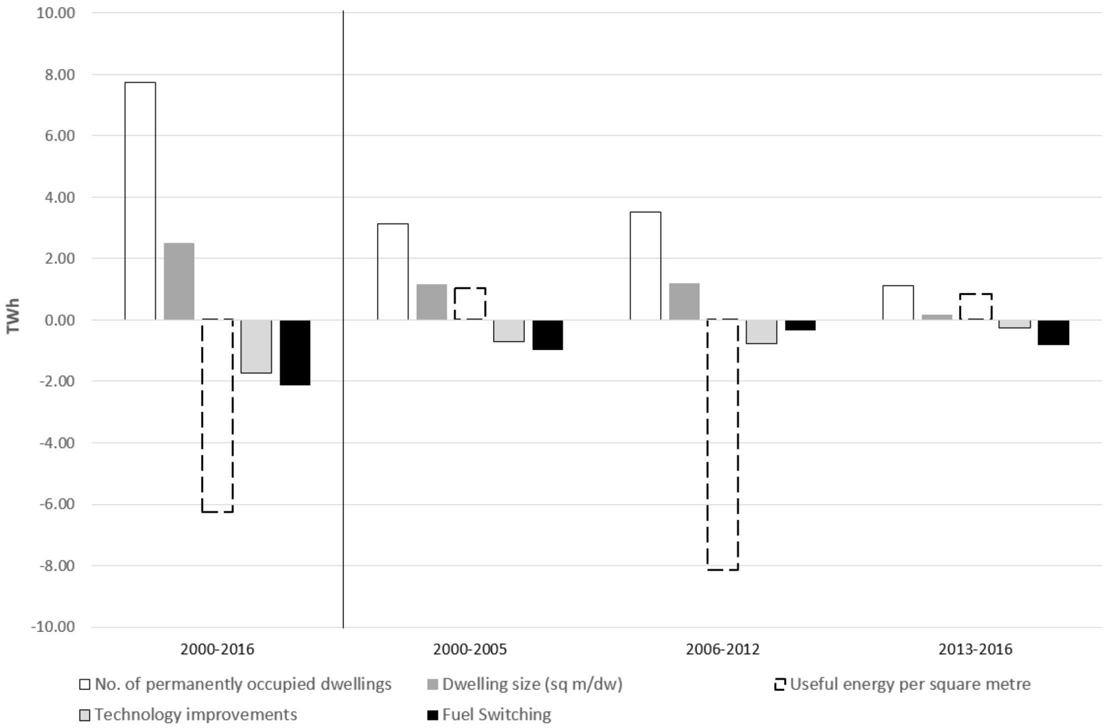
Over most of the 16-year period examined, the impact of fuel switching is towards fuels that are converted more efficiently, which results in less energy consumption and persistent energy savings. However, between 2008 and 2013 there appeared to be a reversal in the fuel switching metric impact, which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

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

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

The factors of disposable income per dwelling (combining the 2nd-4th terms in Equation 2) and disposable income per person (combining the 2nd and 3rd terms in Equation 2) provide evidence of a strong influence of the economic recession, with savings only recorded in the period 2008-2011 (note that as a reciprocal term, the interpretation is the inverse of the results). This is corroborated in Figure 2, where net useful energy per square metre savings are 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

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

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	774
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.

The top-down efficiency savings calculated from the LMDI-I decomposition analysis (7,300 GWh from 2006 - 2016) are significantly higher than the energy-efficiency savings estimates in NEEAP 4 achieved by the end of 2016 for residential space heating only savings[17] (4,443 GWh final energy) over the period 2006 to 2016 (DCCAE, 2017b). However, the best period to compare is from 2006-2012, as the useful energy per square metre savings from the LMDI-I analysis in section 6.1 were monotonic in that period and so can be readily accumulated. The results in the left-most column of Table 2 show the top-down LMDI-I useful energy per square metre savings (8,127 GWh) were significantly higher than the bottom-up NEEAP savings (2,256 GWh). When the technology efficiency and useful energy per square metre improvements (i.e. building envelope) are combined, the top-down LMDI-I efficiency savings were 3.9 times greater than the bottom-up NEEAP savings. Table 2 includes additional evidence to that provided by the LMDI-I analysis in section 6.1 that the recession rather than the energy-efficiency retrofitting schemes are driving the overall energy trends.

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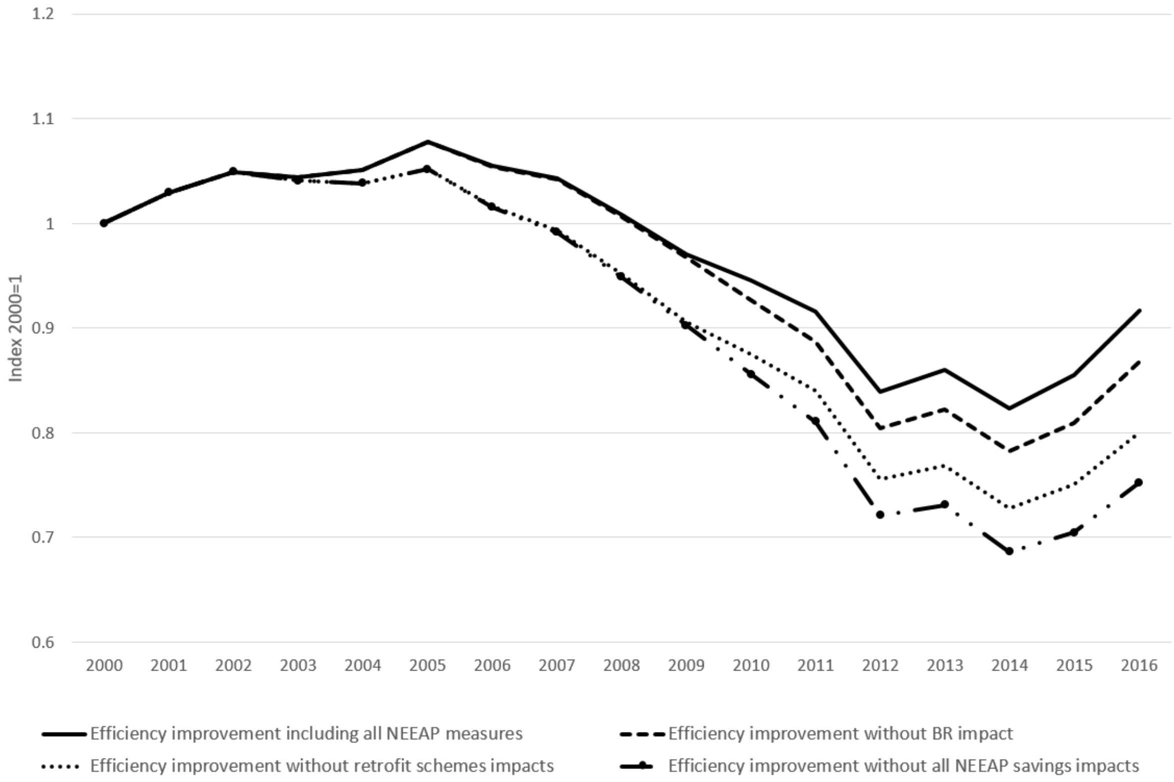
[17] Column 4 of Table 9 in NEEAP 4 excluding the savings from the building regulations related to non-residential buildings, the greener homes scheme and the residential lighting (DCCAE, 2017b). Data for NEEAP tables were revised in 2018 by SEAI, revised data are included in the analysis in this paper.

6.3 Testing the hypothesis that the improvement is due to retrofitting

Counterfactual scenarios were calculated by adding the bottom-up NEEAP energy-efficiency savings to the actual historical residential space-heating energy consumption. That hypothetical demand was then decomposed in a similar manner to the actual historical demand as described in section 6.1. The resulting useful energy per square metre improvement estimates are compared to the results based on actual demand, effectively facilitating a 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, DCCAE 2017b, DCENR 2010, 2012, 2015.

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

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

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

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

7 Discussion

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

The analysis found that the economic recession was responsible for most of the fall in space-heating demand rather than a national energy-efficiency retrofit programme. The CSO also has interesting qualitative survey data relating to energy that provides evidence that the economic recession could be responsible for the sharp drop in energy demand between 2008 and 2012. From July to September 2012 (Q3) a module on the effect on households of the economic recession was included in the Quarterly National Household Survey (QNHS) (CSO, 2013). The questionnaire referred to the twelve months prior to that time period. There was not an explicit reference to energy spend or consumption, but some of the questions asked related to utilities. Households which responded as experiencing difficulty in managing bills and debts during the 12 months prior to the date of interview determined that it was primarily due to higher than expected or additional costs (73%) or loss of income (47%). The majority (90%) of households experiencing financial difficulty cited higher or additional utility bills as one of the reasons they experienced financial difficulty.

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

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

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

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

The question of the extent of fuel switching to solid fuels (coal, peat and wood) in homes with oil central heating at times of high oil prices and or economic hardship also requires further data and investigation. The general perception is that solid fuels are cheap, but as they are used in less efficient technologies (open fires or stoves) the actual price paid in kilowatt hour (kWh) of heat is often more than it would be if that heat was produced from an oil or natural gas central heating boiler[18]. Education or information campaigns could help to change usage patterns of secondary fuels based on value for money and improving air quality within homes.

8 Summary and Conclusions

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

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

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

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

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[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.

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

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

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

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References

ANG, B. W. 2015. LMDI decomposition approach: A guide for implementation. Energy Policy, 86, 233-238.

ANG, B. W. , 2012. A Simple Guide to LMDI decomposition Analysis. Available at: https://www.isem.nus.edu.sg/staff/angbw/pdf/A_Simple_Guide_to_LMDI.pdf

ANG, B. W. 2004. Decomposition analysis for policymaking in energy: which is the preferred method? Energy Policy, 32, 1131-1139.

ANG, B. W. and LIU, F. L. 2001. A new energy decomposition method: perfect in decomposition and consistent in aggregation. Energy. Volume 26, Issue 6, June 2001, Pages 537–548. https://doi.org/10.1016/S0360-5442(01)00022-6

BUILDING RESEARCH ESTABLISHMENT(BRE), 2001, Standard Assessment Procedures (SAP) Energy Rating Manual 2001. Available from https://www.bre.co.uk/

BYRNE, A., BYRNE, G., O’DONNELL, G. & ROBINSON, A. 2016. Case studies of cavity and external wall insulation retrofitted under the Irish Home Energy Saving Scheme: Technical analysis and occupant perspectives. *Energy and Buildings,* 130**,** 420-433.

COLLINS, M. & CURTIS, J. 2017. Value for money in energy efficiency retrofits in Ireland: grant provider and grant recipients. *Applied Economics,* 49**,** 5245-5267.

CSO (Central Statistics Office), 2017a, N1607: T07 Gross National Disposable Income and its Use by Item and Year. Available from: www.cso.ie/px/pxeirestat/statire/SelectTable/Omrade0.asp?Planguage=0

CSO, 2017b, Table E4012 Private Households in Permanent Housing Units 2011 to 2016 by County and City, CensusYear and Type of Private Accommodation (2011-2016). Available from: www.cso.ie/px/pxeirestat/statire/SelectTable/Omrade0.asp?Planguage=0

CSO, 2017c, Table E4003 Average Number of Persons per Private Household 2011 to 2016 by County and City, CensusYear and Statistic (2011-2016). Available from: www.cso.ie/px/pxeirestat/statire/SelectTable/Omrade0.asp?Planguage=0

CSO, 2017d, Table BHQ09 Total Floored Area for which Permission Granted in New Construction and Extensions by Type of Development, Region, Quarter and Functional Category (2009Q1-2017Q3). Available from: www.cso.ie/px/pxeirestat/statire/SelectTable/Omrade0.asp?Planguage=0

CSO, 2017e, NAH14: T14 Consumption of Personal Income (except Taxes on Personal Income and Wealth) (excluding FISIM) at Constant Market Prices (chain linked annually and referenced to 2009) by Year and Item. Available from: https://www.cso.ie/px/pxeirestat/statire/SelectVarVal/Define.asp?MainTable=NAH14&PLanguage=0&PXSId=0

CSO, 2017f, N1613: T13 Consumption of Personal Income at Current Market Prices. Available from: www.cso.ie/px/pxeirestat/statire/SelectTable/Omrade0.asp?Planguage=0

CSO, 2017g, Census 2016. Available from: www.cso.ie/en/csolatestnews/presspages/2017/census2016summaryresults-part1/

CSO, 2016, Household Budget Survey 2015 to 2016. Available from: https://www.cso.ie/px/pxeirestat/Database/eirestat/Household%20Budget%20Survey%202015%20to%202016/Household%20Budget%20Survey%202015%20to%202016_statbank.asp?

CSO, 2013, Quarter National Households Survey. Available from: www.cso.ie

CSO, 2012a, Census 2011. Available from: http://www.cso.ie/en/census/census2011reports/

DCCAE (Department of Communications, Climate Action and Environment – formerly DCENR), 2017a, Focussed Policy Assessment: SEAI Better Energy Homes 2009 – 2015. Available from: https://www.dccae.gov.ie/en-ie/news-and-media/publications/Documents/23/SEAI%20FPA%20Better%20Energy%20Homes%202009%20-%202015.pdf

DCCAE, 2017b, National Energy Efficiency Action Plan 4, 2017 – 2020. Available from: http://www.dccae.gov.ie/documents/NEEAP%204.pdf

DCENR (now DCCAE), 2015, National Energy Efficiency Action Plan 3 2014. Available from: https://www.dccae.gov.ie/documents/NEEAP%203.pdf

DCENR (now DCCAE), 2012, Ireland's Second National Energy Efficiency Action Plan to 2020. Available from: https://www.dccae.gov.ie/documents/NEEAP%202.pdf

DCENR (now DCCAE), 2010, Maximising Ireland's Energy Efficiency. The National Energy Efficiency Action Plan 2009 – 2020. Available from: https://www.dccae.gov.ie/documents/NEEAP%201.pdf

DINEEN, D. & Ó GALLACHÓIR, B. P. 2017. Exploring the range of energy savings likely from energy efficiency retrofit measures in Ireland's residential sector. *Energy*, 121**,** 126-134.

DINEEN, D. & Ó GALLACHÓIR, B. P. 2011. Modelling the impacts of building regulations and a property bubble on residential space and water heating. *Energy and Buildings*, 43**,** 166-178.

ECONOMIDOU, M. 2017. Assessing the progress towards the EU energy efficiency targets using index decomposition analysis, EUR 28710 EN, Publications Office of the European Union, Luxembourg. ISBN 978-92-79-71299-9.

EDELENBOSCH, O. Y., MCCOLLUM, D. L., VAN VUUREN, D. P., BERTRAM, C., CARRARA, S., DALY, H., FUJIMORI, S., KITOUS, A., KYLE, P., Ó BROIN, E. KARKATSOULIS, P. and SANO, F. 2017. Decomposing passenger transport futures: Comparing results of global integrated assessment models. Transportation Research Part D: Transport and Environment, 55, 281-293.

EUROPEAN HEAT PUMP ASSOCIATION (EHPA), 2014, EHPA - European Heat Pump Market Statistics. Available from: http://www.ehpa.org/index.php?id=301&L=0 Accessed on 29 March 2018.

EU, 2006, Directive 2006/32/EC of the European Parliament and of the Council of 5 April 2006 on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC. Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:114:0064:0085:EN:PDF

GRANEL, F., 2003, A Comparative Analysis of Index Decomposition Methods, University of Singapore. Available from: https://core.ac.uk/display/48627014

HAAS, R. 1997. Energy efficiency indicators in the residential sector: What do we know and what has to be ensured? Energy Policy, 25, 789-802.

HUNTER, G., HOYNE, S. & NOONAN, L. 2017. Evaluation of the Space Heating Calculations within the Irish Dwelling Energy Assessment Procedure Using Sensor Measurements from Residential Homes. *Energy Procedia*, 111**,** 181-194.

INTERNATIONAL ENERGY AGENCY (IEA), 2015, Building Energy Performance Metrics. Available from: http://www.iea.org/publications/freepublications/publication/BuildingEnergyPerformanceMetrics.pdf

IEA, 2014a. Energy Efficiency Indicators: Essentials for Policy Making, IEA. Available from:https://www.iea.org/publications/freepublications/publication/IEA_EnergyEfficiencyIndicators_EssentialsforPolicyMaking.pdf

IEA, 2014b. Energy Efficiency Market Report 2014, IEA. Available from: https://www.iea.org/publications/freepublications/publication/energy-efficiency-market-report-2014.html

IEA, 2007. Tracking Industrial Energy Efficiency and CO2 Emissions. Organisation for Economic Cooperation and Development/International Energy Agency (OECD/IEA).

IEA Energy Conservation in Buildings and Community Systems (ECBCS), 2003, Annex 37 - Low exergy systems for heating and cooling of buildings guidebook. Available from: https://www.lowex.net/guidebook/additional_information/annex37_guidebook.pdf

MA, C. and STERN, D. I., 2008. China's changing energy intensity trend: A decomposition analysis. Energy Economics, 30 (3), p.1037 - 1053.

MISHINA, Y. and MUROMACHI, Y. 2012. Revisiting Decomposition Analysis for Carbon Dioxide Emissions from Car Travel Introduction of Modified Laspeyres Index Method. Transportation Research Record, 171-179.

Ó BROIN, E., 2007, Energy Demands of European Buildings: A Mapping of Available Data, Indicators and Models. Thesis for the degree of Master of Science in Industrial Ecology. Chalmers University of Technology.

ODYSSEE-MUREa, 2015a, Decomposition tool. Available from: http://www.indicators.odyssee-mure.eu/decomposition.html

ODYSSEE- MURE, 2015b, Energy Efficiency Trends and Policies in the Household and Tertiary Sectors. Available from: http://www.odyssee-mure.eu/publications/br/energy-efficiency-trends-policies-buildings.pdf

ROGAN, F., CAHILL, C. J. & Ó GALLACHÓIR, B. P. 2012. Decomposition analysis of gas consumption in the residential sector in Ireland. *Energy Policy*, 42, 19-36.

SCHEER, J., CLANCY, M. & NÍ HÓGÁIN, S. 2013. Quantification of energy savings from Ireland's Home Energy Saving scheme: An ex post billing analysis. *Springer*. DOI:10.1007/s12053-012-9164-8.

SEAI (Sustainable Energy Authority of Ireland), 2018a, Energy in the Residential Sector 2018 report. Available from: https://www.seai.ie/resources/publications/Energy-in-the-Residential-Sector-2018.pdf

SEAI, 2018b, National BER Research Tool. Available from: http://www.seai.ie/Your_Building/BER/National_BER_Research_Tool/.

SEAI, 2018c, Domestic Fuel Cost Comparisons Table, Available from: https://www.seai.ie/resources/publications/Domestic-Fuel-Cost-Comparison.pdf

SEAI, 2018d, Energy in Ireland. Available from: https://www.seai.ie/resources/publications/Energy-in-Ireland-2008-Full-report.pdf

SEAI, 2017a, National Energy Balances 1990 to 2016. Available from: https://www.seai.ie/resources/publications/Energy-Statistics-1990-2016.pdf

SERRENHO, A. C., SOUSA, T., WARR, B., AYRES, R. U. & DOMINGOS, T. 2014. Decomposition of useful work intensity: The EU (European Union)-15 countries from 1960 to 2009. Energy, 76, 704-715.

XU, X. Y. & ANG, B. W. 2014. Analysing residential energy consumption using index decomposition analysis. Applied Energy, 113, 342-351.

Appendix 1: Bottom up Energy-Efficiency savings

A time series of the bottom up residential energy efficiency savings estimates is included in Table A1.1. which includes savings from 2000, the savings exceed NEEAP savings which are from policies introduced from 2007, 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).

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

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

Appendix 2: Technology efficiency calculations

The starting point for the technology energy efficiency data in table 5.5 was the UK Standard Assessment 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.

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

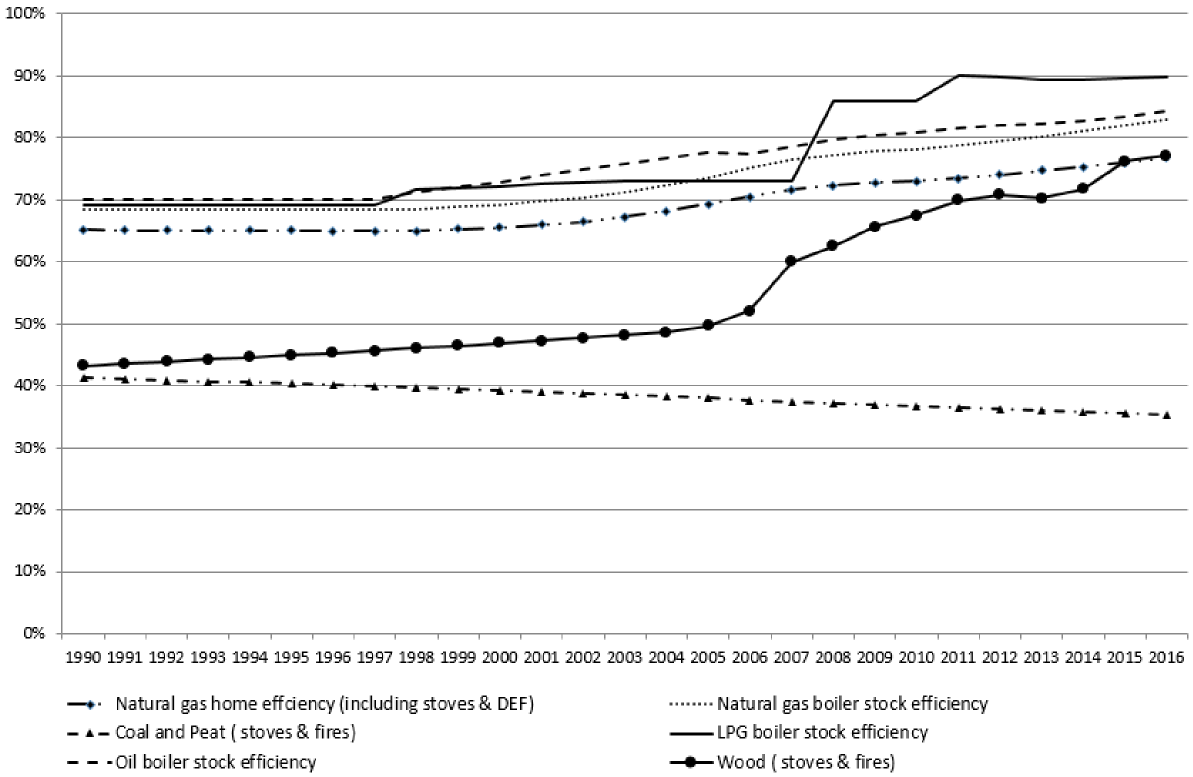
Table A2.2 Asssumptions for Irish space-heating technology efficiency conversion factors

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.

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

Figure 4 Irish space-heating technology efficiency trends over time



Source: Authors' calculations.

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

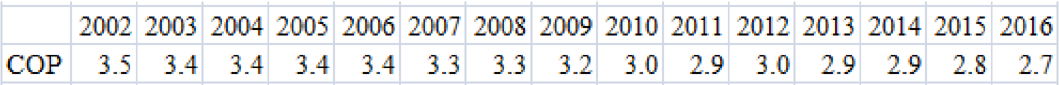
The trend for coal and peat efficiency of conversion, which initially may appear to be counter-intuitive can be explained by large shift from solid fuel based heating prevalent in the early 1990's to central heating. With the shift to central heating the use of back boilers fells as open fires or stoves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

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

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

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

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

Equation A3.1

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

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 i denotes the sub-sector. X represents a factor of an identity equation being decomposed. The function L is the log mean average as described by equation A3.2.

Equation A3.2

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

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

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

Equation A3.3

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

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