# Creation of an improved residential space heating calculation model for the Irish energy performance assessment tool

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## Keywords

energy monitoring, residential sector, Energy Performance of Buildings Directive (EPBD), space heating, heating season, asset rating, existing residential buildings, retrofit, heating schedule

## Abstract

This paper outlines an ongoing study into the energy performance gap (EPG) in domestic dwellings, using real-time wireless sensor data relating to the energy consumption of 95 retrofitted households, situated in rural and town settings in Ireland. The database of room temperatures and electrical energy to the main heating device, enabled the verification of actual, measured heating patterns and corresponding room temperatures, allowing direct comparison to the normative model, the Dwelling Energy Assessment Procedure (DEAP), which is currently used to calculate the energy performance rating of dwellings. The EPG is defined here, as the percentage by which the measured energy consumption of dwellings is above, or below the normative, calculated value. The literature review on the EPG around Europe found that, on average, the measured energy consumption in homes can be 25 % below the calculated consumption and narrowing the EPG would facilitate more accurate energy savings projections for policy planners, energy managers and home owners looking to invest in cost optimal thermal retrofits to reduce both carbon emissions and outlay on energy. This paper describes the extraction and formulation of the relevant sensor data and proceeds to analyse the heating schedules and rest-of-home room temperatures in an effort to strengthen the DEAP model by focussing on the space heating aspect alone, which is shown to be the largest cause of the gap. The results will be statistically verified and directly compared to the current assumptions on the heating schedule and set point room temperatures in DEAP. Sensor-derived information on secondary heating will also be available. DEAP assumes that primary heating systems are used for 56 hours per week during the heating season with 10 % of the space heating coming from secondary sources along with a maintained internal rest-of-home temperature of 18 °C during heating periods. The research expects to prove that the actual, measured values will differ significantly from these assumptions. This paper presents the mid-term research findings which will conclude in January 2016.

## Introduction

The two-year energy monitoring phase of the EU co-funded SERVE (Sustainable Energy for the Rural Village Environment) project was completed in July 2013, having used wireless sensor networks to record room temperatures, space heating fuel use, hot water and electricity consumption, in close to 100 retrofitted households in a rural village and town setting of North Tipperary in Ireland (SERVE, 2012). During the SERVE project the implementation of the Energy Performance of Buildings Directive (EPBD) in relation to issuing of Energy Performance Certificates (EPCs) was commenced in Ireland, which instructed member countries to calculate or measure, the energy consumption (and associated $CO_2$ emissions) of buildings for sale, rent or under construction, throughout the 28 EU member states[1]. Most countries opted for a normative (calculation) model for domestic buildings and were given some flexibility

1. Norway also opted into the EPBD.

to tailor their approach to national requirements for building regulations, comfort levels and climate (Directive 2010/31/EU [recast])

Research in other countries has identified that EPCs have been increasingly inaccurate for dwellings with high energy consumption profiles e.g. older dwellings with few energy efficiency measures implemented, such as roof/wall insulation, boiler or window upgrades (Knissel and Loga, 2006), (Cayre, 2011), (Sunikka-Blank and Galvin, 2012), (Tigchelaar et al., 2011),(Ballarini and Corrado, 2009), (Audenaert et al., 2011), (Majcen et al., 2013). This has been a European-wide phenomenon and the studies have shown that the largest discrepancy is the gap between the modelled and actual energy required for *space heating* in households (Majcen et al., 2013). In Ireland, the EPBD-directed energy consumption of domestic dwellings, which excludes a large quantity household electrical use[2], is calculated by the Dwelling Energy Assessment Procedure and is based on a number of standard assumptions, including a daily heating schedule, fixed at 8 hours, a fixed proportion, usually 10 %, of secondary heating and a set-point rest-of-home (RoH) temperature of 18 °C.

The houses in this study all utilised oil fired central heating as their main space heating system, with most having taken up the SERVE grant-offer[3] to upgrade to a more modern and efficient condensing oil boiler (with zoned space and hot water control) along with cavity wall and attic insulation. Paper surveys and fuel logs were also carried out, to discern the occupants' primary and secondary heating habits. The majority of the monitored houses were two-storey detached or semi-detached dwellings, with the remainder being one-storey detached homes and two terraced houses, with a mean floor area of 170 square metres. Over half (57 %) of the houses were situated in a rural town (population 8,000) with the remainder located further into the countryside. Detached and semi-detached houses make up 40 % and 25 % of all houses in Ireland, respectively and there is a 64/36 % urban/rural proportion of all houses (Central Statistics Office, 2012).

The data set collated under SERVE is one of the largest real-time monitoring samples on domestic household energy, of its kind in Ireland to date. In many cases (houses), the extent of the monitoring period extended over two full heating seasons, which are defined as running from the 1st October to the 31st of May, each year.

The methodology employed and analysis of the sensor data are covered including data integrity with regard to missing data, along with some mid-term findings and tentative conclusions.

The first section defines this paper's use of the energy performance gap (EPG) followed by an overview of the related research papers which quantify the EPG relative to the samples studied. DEAP is then introduced followed by an outline of the SERVE project. A section on the retrieval of the sensor data is then followed by the data analysis on the heating schedule and rest-of-home temperatures, taking note of the limitations of the results. The paper ends with a discussion of the results and conclusions.

2. Only the electricity for hot water production, lighting, space heating pumps and ventilation fans are included in the EPBD.

3. Aided by the EU Concerto initiative and co-ordinated by the *Tipperary Rural and Business Development Institute* (now *LIT Tipperary*).

## Energy Performance Gap

The EPG, in this paper, describes what percentage the actual energy consumption is higher or lower than the calculated, predicted value, and is given by:

$$EPG = \frac{\Delta(M - C)}{C}(\%)$$

where C is the calculated energy consumption and M is the measured, or actual energy consumption. The numerator gives the difference between M and C, so that if M was less than C, the measured energy consumption would be below the calculated consumption by the specified percent. This definition differs from (Galvin, 2014) who uses the EPG as a descriptor only for the over-consumption of energy in either new-builds or after a retrofitting action, while preferring to use the term *prebound* for the under-consumption of a pre-retrofit building. Since it is possible for the measured energy consumption to remain lower than the calculated value after a shallow retrofit, the EPG is used here as an umbrella term, to describe all gaps between M and C.

### QUANTIFYING THE EPG

In the Netherlands, Majcen et al (2013) published a detailed account, segregating gas usage from electricity for 200,000 existing houses, concluding that for households with energy bands C to G, the measured *gas* usage was lower than that calculated on average, with the gap increasing to around 50 % for G-rated homes. The *electricity* consumption was approximately a third of the total delivered energy consumption, on average, for dwellings with energy label C to G but included electricity for *all* uses, showing that the household energy consumption for space and water heating is, generally much larger than the modelled electrical energy usage in the C to G label range, although in primary energy terms the proportion of electricity would increase.

Figure 1 shows the average EPG from studies conducted throughout Europe. Most studies, looked at the energy required for space heating and hot water production using natural gas fuel, via utility bills, and all studies disregarded electrical use.

All but one of the research papers recorded a lesser, measured energy consumption in comparison to the normative model, ranging from +8 % to -43 %, with an average of -25 % across all 17 studies. Newly built, low energy buildings can show the opposite effect, but none are considered in these studies. It should be noted that countries use differing calculation methods, but the trend is clear, irrespective of the variations in the models: the EPG is significantly high, so that European, national and local models for assessing retrofitting actions substantially overestimate the energy and resulting $CO_2$ savings. In general as the energy performance decreases i.e. moves towards the G band, the majority of houses use progressively less energy compared to the normative model.

## Irish Energy Performance Assessment Tool: DEAP

The Dwelling Energy Assessment Procedure (DEAP) is the nationally approved calculation method behind the reporting of the energy performance of residential buildings and compliance to specific building regulations in Ireland. The data behind the EPCs, created by DEAP, are held on a publicly accessible Building Energy Rating (BER) database, and administered by the Sustainable Energy Authority of Ireland (SEAI). DEAP provides for a BER certificate showing an energy class, from A to G, and a specific energy rating given in kWh/m² year, indicating the level of energy consumption the relevant house would expect to use, given standard patterns of dwelling occupancy and comfort levels (SEAI, 2012). Figure 2 shows the energy bands and the calculated energy consumption levels, in kWh/m² year.

For the space heating aspect of the model, DEAP relies on a series of standard assumptions, including a 56 hour, weekly heating schedule over the 8 month heating season (October to May, inclusive) and living area and rest-of-home (RoH) set point temperatures of 21 °C and 18 °C respectively. The model calculates the expected energy consumption, on a monthly basis, to maintain a floor space-weighted average target temperature which is applied to the whole normally-heated area of a dwelling, taking into account the thermal properties and details of the main and secondary space heating systems. A fixed proportion (10 %) of the total space heating energy is assigned to a secondary heating source, such as a wood burning stove, open fire or fixed gas heater. DEAP is required to balance ease of use for BER assessors with enough complexity to give a reasonable approximation of the expected energy consumption of dwellings across the A to G band spectrum(SEAI, 2012). The SERVE monitoring phase provided a unique opportunity to assess *actual* energy consumption for comparison with DEAP, resulting in an average actual energy consumption of 13 % less than DEAP's calculations, which was explained partly by high use of secondary heat sources, such as wood, and an indication that household temperatures were less than the model assumes (Petersen et al., 2012).

## SERVE Project

The SERVE (Sustainable Energy in a Rural Village Environment) project was set up to promote a community-led example of sustainable development in rural Ireland and involved the installation of sustainable energy technologies in 400 existing buildings in the North Tipperary region. Following the retrofitting of the existing houses, energy monitoring systems were installed in nearly 100 of these homes to record heating data and electrical energy consumption, using state-of-the-art wireless sensor technology. The SERVE project also supported the establishment of Ireland's first Eco-village of low-energy buildings, run from a wood/solar thermal district heating scheme (SPIL, 2015) and to the development of a three year SustainCo Project advocating Nearly Zero Energy Buildings (SustainCo, 2015). The monitoring phase of the SERVE project was conducted after heating system and insulation upgrades were complete and the homeowners were issued with BER certificates before and after the retrofitting actions.

### MONITORING PHASE

The monitoring phase of the SERVE project ran from March 2011 to July 2013 collating information from over 600 wireless sensors which were installed into 95 houses though only 300 of the devices were relevant to the present research. The data from the wireless sensors was communicated, via a household's Wi-

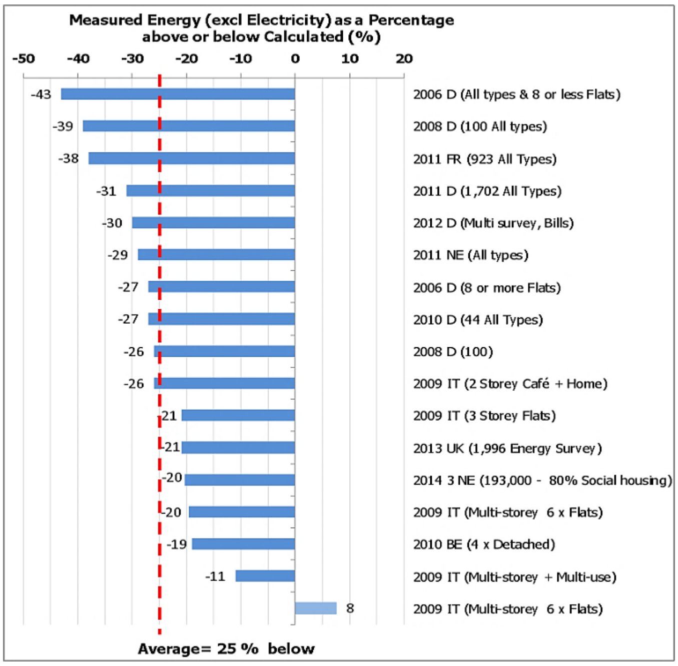


*Figure 1. Energy Performance Gap from Literature Review.*

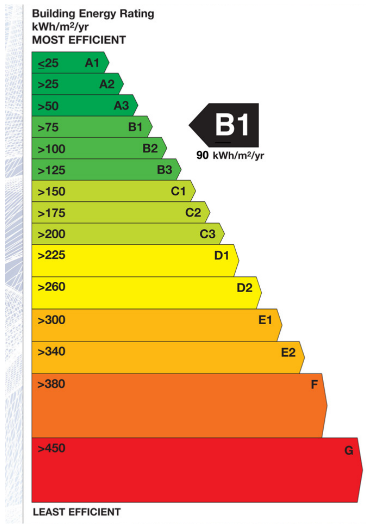


*Figure 2. Energy Consumption (kWh/m² year) and Energy Class (A to G) for BER Certificate. (Reprinted with permission from SEAI.)*

Fi network, to a locally mounted gateway micro-computer, which then transferred the information onto a remote database server and, while some households had many monitoring points, only three of the sensors per household are of interest to this study:

- Electrical energy sensor, measuring the cumulative *watt-hours*, in mostly one-hour intervals, delivered to the burner of an oil-fired central heating boiler, using a ZEM30 wireless sensor.[4]

4. All wireless sensors and associated equipment was provided by Episensor Ltd, Limerick, Ireland.

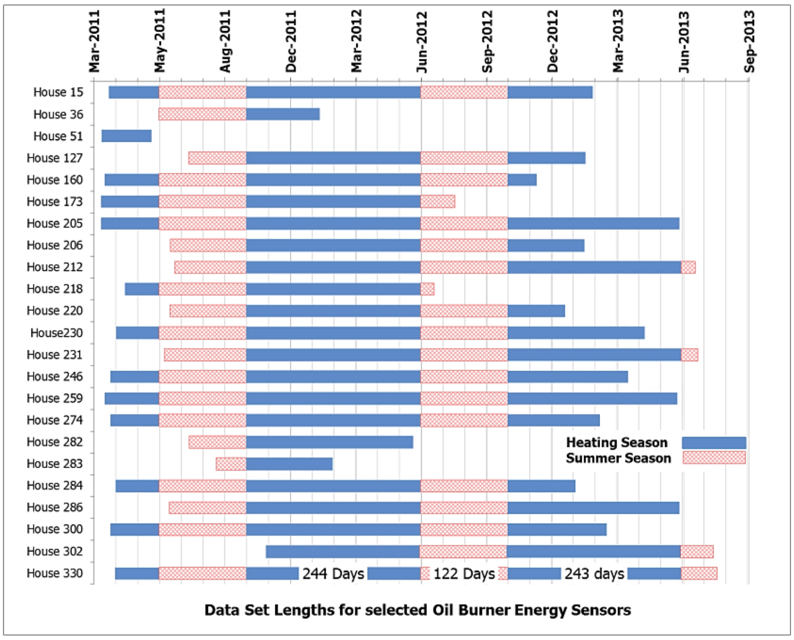


*Figure 3. Monitoring Periods of Selected Houses.*

- TES11 temperature sensor located in main living area, taking half-hourly temperature readings close to the secondary heating source.
- TES11 temperature sensor located in the main bedroom of the house, representing the rest-of-home temperature, recorded at, again, mostly hourly intervals.

Monitoring start dates for each house differed due to the large number of houses involved, completion dates of retrofit works and the finding of mutually convenient meeting times for installers of the sensors and householders (Petersen et al., 2012). Figure 3 shows the extents of a selection of the ZEM30 (energy to the boiler) datasets, indicating the first full, 244-day heating season (solid bar), then the 122-day summer period (hatched bars), followed by the second, 243-day heating season. The top axis of the chart shows the start and end dates, but does not display any data gaps, which occurred quite frequently with the watt-hour sensors.

## Sensor Data Retrieval

The sensor data was downloaded from the server into a 4.7 GB csv file, containing 33 million records. MS Excel and Minitab could not accommodate files of such size, but the IBM SPSS version 22.0 software package was able to store the entire file, and after applying a case number to each record (case), it was saved as a 5.9 GB SPSS database file.

The TES11 (temperature) and ZEM30 (boiler) data were then identified and extracted into separate SPSS files, to speed up data processing and individual sensor data was then saved into SPSS and MS Excel files for further analysis. A spreadsheet template was designed to automatically produce analytical graphics once the sensor data was copied over. Charts showing monthly availability, room temperatures and heating patterns versus degree days were generated, allowing for the selection of the quality datasets for further analysis. A key feature of the database of heating hours and room temperatures was how well they both track the degree days, when plotted; the heating hours increase with degree days while room temperatures generally fall with increasing degree days. This had the effect of adding credibility to the sensor data and the monitoring phase in general (Figure 4).

## Analysis of the Sensor Data

The analysis of the heating schedule (oil boiler on-hours) and the room temperatures have been approached differently due to the nature of each measurement and the hourly sampling interval of most datasets[5]. The heating schedule of occupants results in their required or accepted room temperatures, although other habits such as ventilation and use of sunshine also play a part, however to determine the heating patterns involves capturing the times when the heating system is in operation, which may only be for a small fraction of the day, typically but not universally, less than half the day is of interest. If one or more measurements are missing, it can affect the day's overall result considerably. In contrast, each of the room temperature measurements is of interest and is less sensitive to some missing data, since the mean room temperature would not be affected significantly by one or two missing data points. Following this, the heating schedule analysis was initially performed on the datasets, from the houses, which extended through both heating seasons to enable comparison between the two, capturing the variety of warmer and cooler months on a continual basis. This method resulted in a sample size of only 14 datasets so a separate analysis was conducted on all months (not necessarily consecutive) which had high data availability, bringing the number of contributing datasets to twenty-one.

The rest-of-home temperature data was less prone to missing values, which permitted the use of 54 datasets (houses) for the first heating season, and 28 for the second.

5. Six of the watt-hour sensors were set (accidentally) to a 15-minute sampling time.

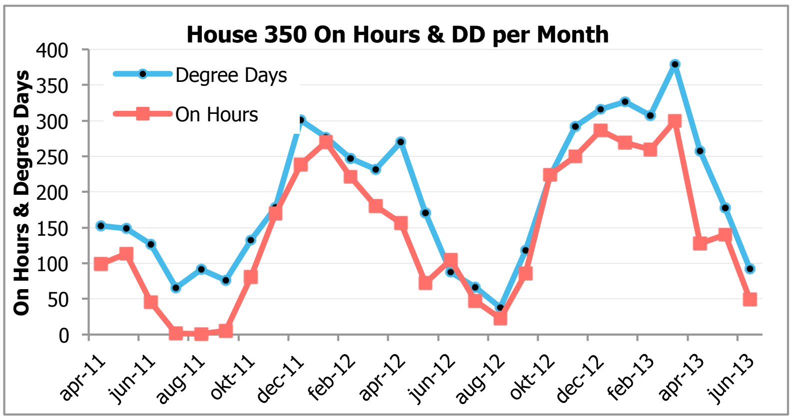


*Figure 4. Example of Boiler On-hours Tracking Degree Days.*

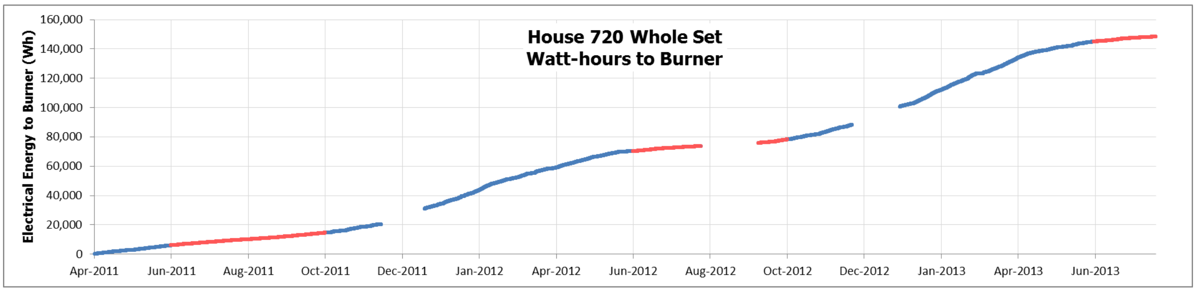


*Figure 5. Dataset with Continuous Data Gaps.*

#### DATA GAPS

Data gaps were a common feature in the boiler datasets and were often due to an internet or Wi-Fi communication break, but also due to house occupants sometimes unplugging the necessary equipment causing the sensor or modem to power down The sensors did not always properly re-set after such interruptions, which may have gone unnoticed for some days or weeks. Measures have been attempted to achieve an approximation by using a Wh-per-degree day factor, but this had limited effect when tested on existing datasets. The variety of heating patterns, along with markedly different (5 to 100 Wh) watt-hours per hour within and between datasets proved that this approach was too inaccurate to continue. The preference was to report a maximum, actual heating schedule from the good quality datasets, that covers as many months, evenly, over the two year period, so no further attempt has been made to estimate any missing data at this stage although it may still be possible to estimate shorter data gaps from the two temperature sensors in the RoH and the living area, but with due caution. The provider of the sensors has since improved their design so that the sensors can log the measurements, when communications are down, and re-send the information when the network is repaired (Episensor, 2014)

## Heating Schedule Analysis

The objective of this part of the analysis was to arrive at an estimation of actual heating schedules, in heating *on-hours per month* (or per heating season), in order to compare with the assumption in the DEAP model of 8 on-hours per day, during the October to May heating season. A shorter heating schedule leads to a reduction in fuel use by householders and would narrow the energy performance gap for less thermally efficient homes.

#### HEATING SCHEDULE DATA VALIDATION

Validation of a boiler energy dataset began with a plot of the entire monitoring interval, to check on the seasonal change in the operational hours of the heating system and to identify obvious gaps in the data. A potentially good dataset will have a gently increasing, or flat profile, in the summer months, followed by a sharper rise in the cumulative watt-hours as the heating season developed. A dataset with obvious gaps is shown in Figure 5 with the summer months (June to September) highlighted.

The spreadsheet template generated a column chart showing the percentage of the data that was available for each month. One such dataset is displayed in Figure 6, again showing the summer months highlighted. The start and end months are filled with cross-bars, indicating that only a portion of the first or last month was available, due to the sensor installation and removal dates. A further plot was automatically generated, showing the seasonal change of the watt-hours plotted against degree days (Figure 7).

The local degree days are listed later, showing that March 2013 and November 2012 were markedly colder than the 30-year long term average, while other outliers can be identified which may indicate when householders were on holiday.

#### HEATING SCHEDULE (BOILER OPERATIONAL ON-HOURS) RESULTS

The ZEM30 sensor data was found for 91 individual houses. Presently, 21 datasets have been identified which are helpful to the analysis with fourteen of these datasets having 12 or more uninterrupted months of, mostly, hourly samples. Nearly all of

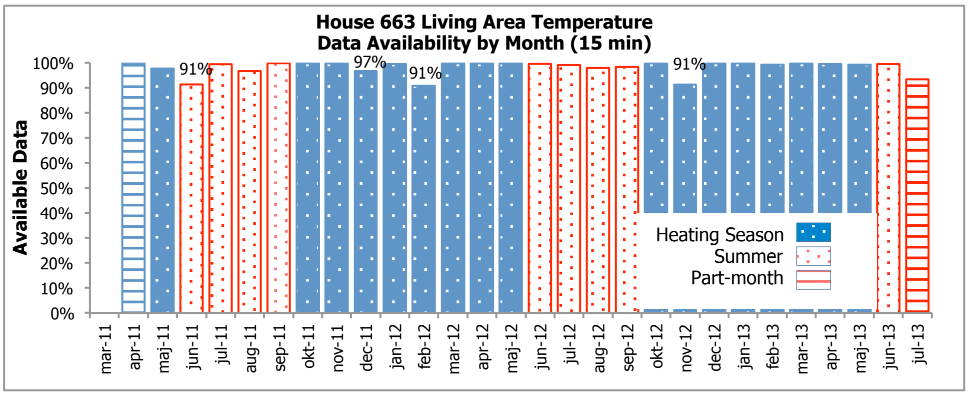


*Figure 6. Data Availability by Month (RoH shown, but similar to Boiler On-hours).*

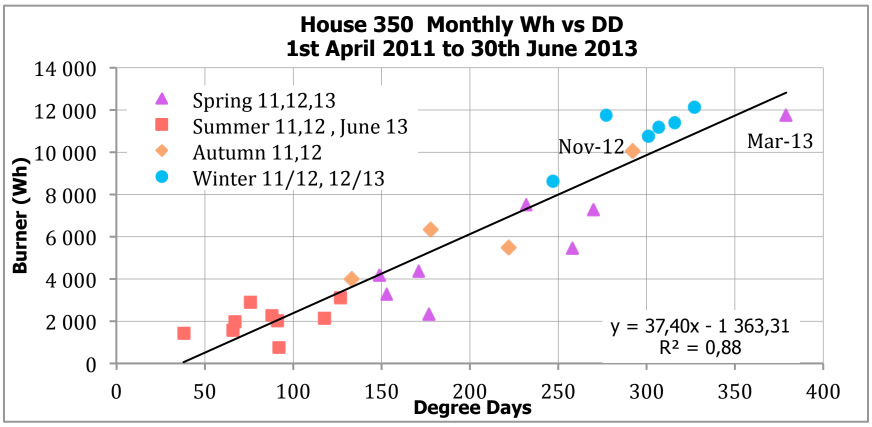


*Figure 7. Burner Watt-hours vs. Degree Days, Seasonal Display.*

the high availability months (over 190) taken from the fourteen houses had at least 95 % of the expected time-stamped data (5 % missing equates to 1.55 missing days at most), with over 150 months having greater than 99 % of the expected data available. The remaining good sets had nearly 100 % data availability for many months, but the full months were interspersed with months with considerable data missing.

The following analysis contrasts the heating schedules between the first, warmer heating season (HS1) and a second, much cooler one (HS2) which is shown by comparing the degree days in each season to the 30-year long term average (LTA)[6] displayed in Table 1 (Met Eireann, 2015). Heating season 1 had 179 less degree days than the LTA, indicating a warmer season while HS2 had 290 more degree days than the LTA.

The 14 sensor datasets that covered the majority of both heating seasons have been analysed to check how they compared to the assumed heating schedule in DEAP, with the results shown in Figure 8.

The horizontal axis shows the hours that DEAP expects a heating system to be in operation, which is 8 hours per day, for 28 to 31-day months – the 224 hour mark represents February 2013. The vertical axis shows the actual on-hours, for each of the 14 houses for each month. There are 12 out of 112 "house-months" (points) missing from the first heating season and 7 months missing from the second, leaving 205 valid data points. The majority (80 %) of the house-months for the first heating season registered below what DEAP expects, but for the much cooler second heating season, less than 60 % of the house-months saw the heating systems using less than DEAP assumes.

Table 2 provides a month by month breakdown of how the 14 houses compared to DEAP over both heating seasons. Heating season 1 is shown on the left half of the table. Column B shows the number of houses (out of the total number of houses that contributed to the particular month, shown in column A) which used less than DEAP for that particular month, while columns C to G show by what percentages below DEAP the actual boiler on-hours were, for example, cell G1 shows that 5 out of (11) contributing houses used their heating systems more than 50 % *less* than DEAP assumes for October 2011.

As may be expected, the warmer months, closer to summer, see many households using their heating systems (much) less than the DEAP model assumes, while these households use closer to, or even exceed the DEAP model for the cooler months. Over the entire (first) 8-month heating season (HS1) one household used 19 % more than DEAP assumes while another used 70 % less, with an average heating schedule of 25 to 32 % below the DEAP model[7]. For the second heating season

6. Recorded at a weather station within 30 kilometres from the monitored houses

7. All 14 houses with some low availability months excluded produced the 25 % figure, while 7 of the 14 houses with all months available generated the 32 % figure.

**Table 1. Degree Day Comparison to Long Term Average.**

| | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Total | Tot-LTA | % Difference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **HS1** 2011–12 | 133 | 178 | 301 | 277 | 247 | 232 | 270 | 171 | **1,809** | -179 | -9.0 % |
| **HS2** 2012–13 | 222 | 292 | 316 | 327 | 307 | 379 | 258 | 177 | **2,278** | 290 | +14.6 % |
| **LTA** | 172 | 248 | 306 | 324 | 289 | 272 | 221 | 156 | **1,988** | | |

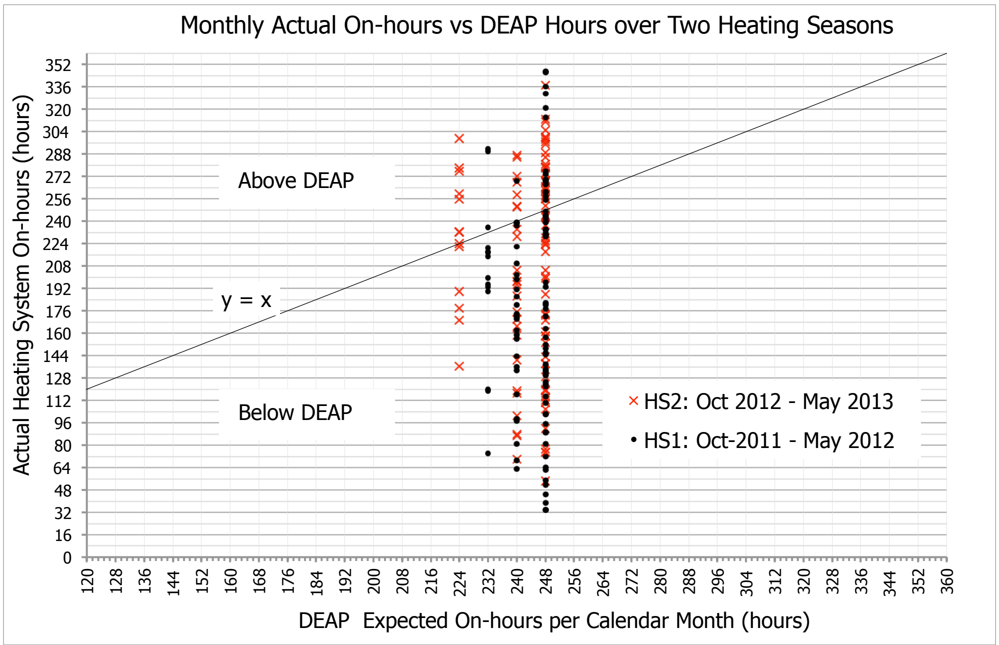


*Figure 8. Actual versus Theoretical Heating System Use.*

**Table 2. Heating Schedule – number of houses (with percentage) below DEAP.**

| | | A | B | C | D | E | F | G | | H | I | J | K | L | M | N |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Contributing Houses | Heaitng Season 1 | | | | | | | Contributing Houses | Heaitng Season 2 | | | | | |
| | | | **<DEAP** | >10% | >20% | >30% | >40% | >50% | | | **<DEAP** | >10% | >20% | >30% | >40% | >50% |
| 1 | Oct-11 | (11) | 10 | 10 | 10 | 9 | 7 | 5 | Oct-12 | (13) | 11 | 9 | 8 | 6 | 5 | 3 |
| 2 | Nov-11 | (12) | 12 | 9 | 8 | 5 | 4 | 3 | Nov-12 | (13) | 7 | 6 | 3 | 3 | 1 | 1 |
| 3 | Dec-11 | (12) | 6 | 2 | 2 | 1 | 1 | 1 | Dec-12 | (13) | 5 | 4 | 2 | 2 | 1 | 1 |
| 4 | Jan-12 | (14) | 6 | 3 | 3 | 3 | 3 | 2 | Jan-13 | (14) | 4 | 2 | 2 | 2 | 0 | 0 |
| 5 | Feb-12 | (14) | 11 | 7 | 3 | 3 | 3 | 1 | Feb-13 | (14) | 6 | 4 | 3 | 1 | 1 | 0 |
| 6 | Mar-12 | (12) | 11 | 9 | 9 | 6 | 4 | 3 | Mar-13 | (13) | 5 | 3 | 2 | 2 | 2 | 0 |
| 7 | Apr-12 | (12) | 11 | 10 | 8 | 6 | 4 | 2 | Apr-13 | (13) | 12 | 11 | 10 | 7 | 7 | 5 |
| 8 | May-12 | (13) | 13 | 12 | 12 | 12 | 11 | 7 | May-13 | (12) | 12 | 12 | 11 | 11 | 9 | 8 |
| | | TOTALS: | 80 | 62 | 55 | 45 | 37 | 24 | | TOTALS: | 62 | 51 | 41 | 34 | 26 | 18 |
| | | % of Months: | **80%** | **62%** | **55%** | **45%** | **37%** | **24%** | | % of Months: | **59%** | **49%** | **39%** | **32%** | **25%** | **17%** |
| | | | | Total Months: | | 100 | | | | | | Total Months: | | 105 | | |

(HS2) the maximum was 20 % above, the minimum was 47 % below with an average on-hours of 13 % below the normative model.

An alternative approach collated the datasets with a high availability of data on a monthly basis, not necessarily consecutive. The number of houses (n) contributing to each month is shown in Table 3 which is plotted in degree day (local) order. A maximum of 20 houses contributed to some months with an average of 17 houses per month. The number of houses that had a higher heating intensity than DEAP models (**n Above**) clearly rises as temperatures drop, but the average boiler on-hours per day rarely rises above 8, as the last column shows. The mean daily heating schedule was calculated to be 6.2 hours per day, or around 43 hours per week. This is suspected to be a high figure due to the accepted inaccuracies surrounding the first and last operational hours, as suggested by the shorter schedule calculated from the 15-minute interval set. Nevertheless, the actual heating schedule works out to be 22 % less than the DEAP assumption, on average, although the small sample size of 11 to 20 houses must still be borne in mind.

Figure 9 summarises the monthly on-hours for both heating seasons, noting that the DEAP expected heating schedule

**Table 3. Monthly Comparison of Boiler On-hours per Day.**

| LTA Deg-Day | Local DD | Month | n Above | n Below | Mean On Hours | DEAP Hours | Mean to DEAP (%) | n | Mean Hours Per Day |
|---|---|---|---|---|---|---|---|---|---|
| 172 | 133 | **Oct-11** | 0 | 17 | 97 | 248 | -61 % | 17 | 3.14 |
| 156 | 171 | **May-12** | 1 | 17 | 134 | 248 | -46 % | 18 | 4.34 |
| 156 | 177 | **May-13** | 1 | 10 | 115 | 248 | -54 % | 11 | 3.70 |
| 248 | 178 | **Nov-11** | 1 | 19 | 153 | 240 | -36 % | 20 | 5.12 |
| 172 | 222 | **Oct-12** | 4 | 15 | 185 | 248 | -26 % | 19 | 5.96 |
| 272 | 232 | **Mar-12** | 2 | 17 | 175 | 248 | -29 % | 19 | 5.64 |
| 289 | 247 | **Feb-12** | 3 | 17 | 193 | 232 | -17 % | 20 | 6.64 |
| 221 | 258 | **Apr-13** | 2 | 10 | 145 | 240 | -40 % | 12 | 4.82 |
| 221 | 270 | **Apr-12** | 2 | 17 | 169 | 240 | -29 % | 19 | 5.65 |
| 324 | 277 | **Jan-12** | 9 | 10 | 231 | 248 | -7 % | 19 | 7.46 |
| 248 | 292 | **Nov-12** | 8 | 12 | 190 | 240 | -21 % | 20 | 6.33 |
| 306 | 301 | **Dec-11** | 11 | 9 | 249 | 248 | 0 % | 20 | 8.03 |
| 289 | 307 | **Feb-13** | 5 | 9 | 216 | 224 | -4 % | 14 | 7.71 |
| 306 | 316 | **Dec-12** | 10 | 7 | 265 | 248 | 7 % | 17 | 8.56 |
| 324 | 327 | **Jan-13** | 10 | 6 | 266 | 248 | 7 % | 16 | 8.58 |
| 272 | 379 | **Mar-13** | 9 | 4 | 249 | 248 | 0 % | 13 | 8.02 |
| | | Total: | 78 | 196 | | Mean: | **-22 %** | **17.1** | **6.23 hr/day** |

changes with the day-length of the month shown by the wavy dashed central line. The lower, horizontal dotted line is the average of the mean monthly values, equalling 190 on-hours per month. Degree days and boiler on-hours can use the same scale in this instance.

Figure 9 verifies, that as the degree days rise, then so too does the mean monthly use of heating systems, but it is only when an almost specific "level" of coolness occurs that residents approach the heating schedule assumed in the DEAP model. For this group of houses, that level appears to be when 300 degree days are recorded, although March 2013 would expect to see higher boiler on-hours by this simplistic model.

## Rest-of-Home Temperature Analysis

Temperature sensors were placed in the main bedroom of each house, positioned away from direct sunlight and other heat sources. The DEAP model treats the normally heated space of a dwelling as a single zone and applies an average internal temperature calculated from a floor-weighted average of the two standardised internal temperatures relating to the living area and the rest of the home which is normally heated. While it may have been possible for the main bedroom to be heated to a higher temperature than other non-living areas of a home, it is the purpose of this study to initially prove that the RoH temperature was *lower* than 18 °C and the following analysis attempts to verify this.

### ASSUMPTIONS FOR THE ROH TEMPERATURE DATA ANALYSIS

The assumptions relative to the temperature datasets are:

1. At each recording time, the sensor recorded the representative temperature in the room itself, but also, the representative temperature for the rest-of-home, that is; the remaining bedroom (s), bathrooms, landings, hallway and any other rooms, ordinarily assumed in DEAP
2. The temperature does not vary significantly in between sensor readings, so as to make the recorded temperature unrepresentative of the time period.

### VALIDATION OF THE ROH TEMPERATURES

The SERVE database held records from 92 houses. The data availability was markedly better than that for the energy supply to the oil burner. For each dataset, a scatter plot of the recorded RoH temperatures versus time was generated (Figure 10).

A check was then made on the sampling interval to reveal any large gaps, as shown in Figure 11.

The datasets typically showed a linear relationship between the mean monthly RoH temperature and degree days showing that the rest of the home temperatures drop when outdoor temperatures fall. A dataset reaching low temperatures is shown in Figure 12.

Very few temperature profiles were flat as in Figure 13, suggesting that few occupants tried to maintain a steady, comfortable bedroom temperature throughout the year. These plots help strengthen the validity of the datasets.

### REST-OF-HOME MEAN HEATING SEASON TEMPERATURE RESULTS

For the first heating season (1st October 2011 to 31st May 2012), 54 sensors had more than 90 % of the expected data available for analysis. Since the sample size exceeds 30 then large-sample statistical analysis was empowered, allowing a Z-test of the means of each dataset to be calculated in order to verify an upper bound and confidence interval to estimate the population mean RoH temperature[8]. The mean *8-month heating season*

8. This test relies on the central limit theorem which suggests, when applied to sample means, that the sampling distribution of the sample mean be close to a normal distribution for large sample sizes.

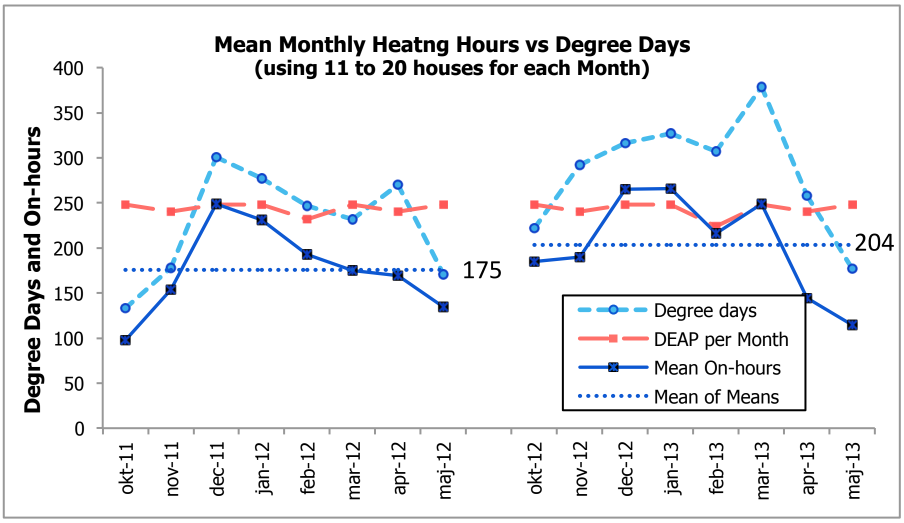


*Figure 9. Summary of Monthly Boiler On-hours.*

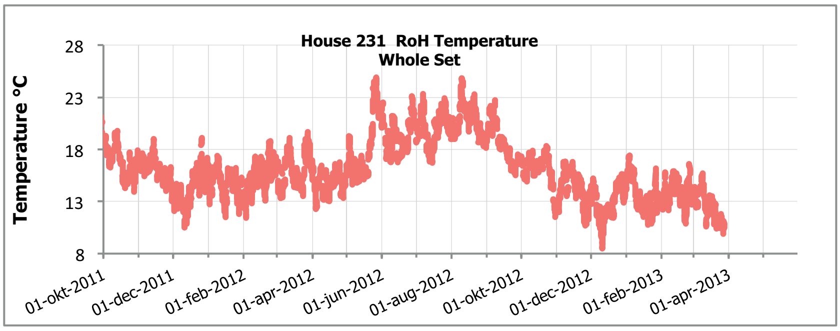


*Figure 10. Whole Temperature Set Check.*

temperature for each of the 54 high-availability datasets was computed and appears in Table 4.

#### Z-test of the first Heating Season Means

While it is preferable to use the overall population standard deviation (σ), the sample standard deviation (s) is acceptable for this study, so from the descriptive statistics, the mean of the 54 means in Table 4 was found to be **16.902 °C** and the sample standard deviation, **s = 1.674 °C.**

Minitab was used to generate the results with the null hypothesis set to *less than* the DEAP model, which uses 18 °C as the expected RoH temperature (Figure 14 and Table 5). The results, given in Table 5 show a *p*-value <0.001, which is highly significant, and together with the 99 % confidence interval (meaning 1 sample of 54 means in a hundred, will see the mean value rise above the upper bound), it can safely be said that the mean rest-of-home temperature is indeed less than 18 °C for the population of houses that the 54 SERVE houses represent. The calculations for the second heating season were not so straightforward.

#### T-test of the second Heating Season Means

Twenty-eight houses were found to have a high availability of data, including 22 houses with more than 95 % of the data available for the second heating season. Only the heating season (October to May) data was stored for statistical analysis with the means shown in Table 6.

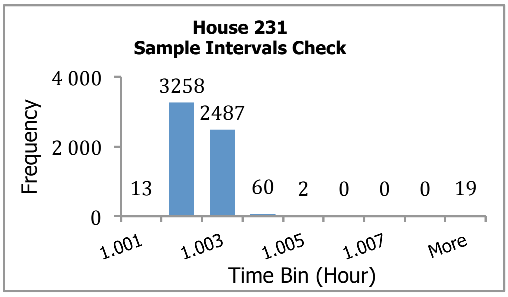


*Figure 11. RoH Temperature Sample Interval.*

Twenty-eight samples is two samples short of becoming a large sample and so a t-test is needed, which requires that the underlying data be distributed close to normal. Minitab was again used to check on the distribution of the raw data, and also to do a normality test. The results are shown in Figure 15.

The distribution of the underlying data is slightly left skewed and the normal probability plot shows that up to around 21 °C, the distribution of the data looks quite normal, but drifts off at higher temperatures. The median value is often preferred as a closer approximation to the central value in skewed distributions, which was 17.1 °C from the descriptive statistics, however, it is thought that this data needs to be re-visited, perhaps by performing a transformation to the data during the next stage of research.

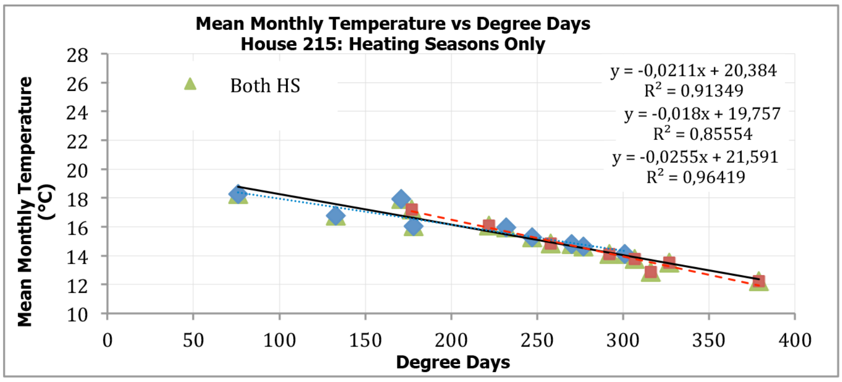


*Figure 12. Mean Monthly RoH Temperature vs. Degree Days.*

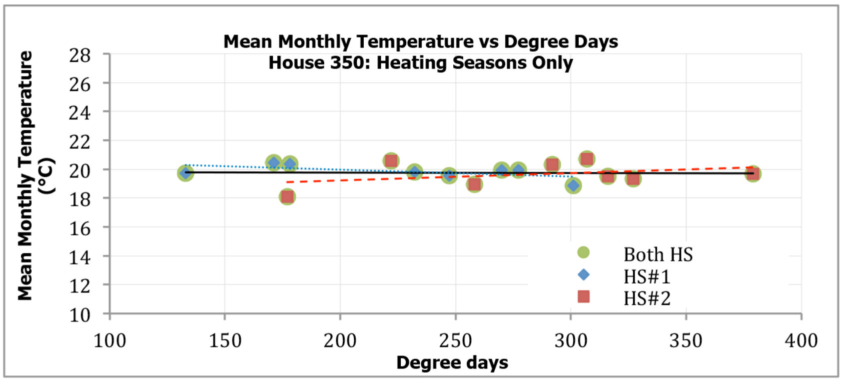


*Figure 13. Flat Profile for RoH Temperature.*

**Table 4. Mean Heating Season Temperatures for HS1 (°C).**

| | | | | | | |
|---|---|---|---|---|---|---|
| 15.78 | 16.41 | 18.54 | 16.90 | 19.90 | 18.04 | 15.66 |
| 17.17 | 19.84 | 16.12 | 19.13 | 14.43 | 16.62 | 15.70 |
| 15.23 | 19.04 | 16.61 | 18.41 | 16.44 | 16.75 | 17.21 |
| 21.98 | 14.65 | 15.65 | 16.36 | 15.19 | 15.15 | 16.25 |
| 17.84 | 14.85 | 20.74 | 18.03 | 18.70 | 16.59 | 16.70 |
| 16.50 | 17.00 | 16.12 | 18.20 | 17.08 | 17.35 | 15.17 |
| 17.45 | 16.17 | 13.17 | 13.83 | 16.92 | 15.50 | 18.03 |
| 16.24 | 16.16 | 17.49 | 17.37 | 18.34 | | |

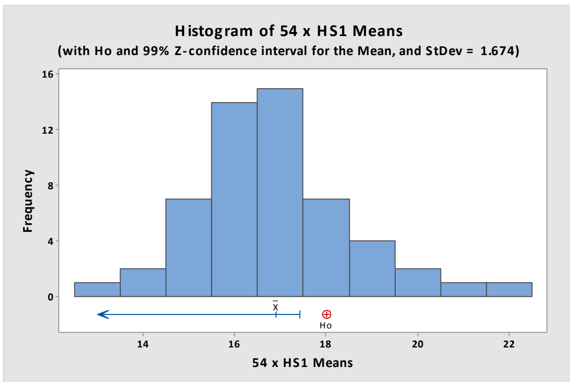


*Figure 14. One-sided Z-test of the Means of 54 × HS1.*

**Table 5. Z-test Results on 54 RoH Temperature Means.**

| Variable | N | Mean | StDev | SE Mean | 99 % Upper Bound | Z | P |
|---|---|---|---|---|---|---|---|
| 54 x HS1 Means | 54 | 16.902 | 1.674 | 0.228 | 17.432 | -4.82 | 0.000 |

**Table 6. Mean Heating Season Temperatures for HS2 (°C).**

| | | | | | | |
|---|---|---|---|---|---|---|
| 14.44 | 15.67 | 15.68 | 17.49 | 14.34 | 16.69 | 19.64 |
| 17.44 | 15.65 | 17.51 | 14.37 | 17.77 | 13.83 | 15.92 |
| 13.75 | 18.39 | 15.00 | 16.12 | 13.76 | 17.81 | 17.36 |
| 16.85 | 16.33 | 16.05 | 13.16 | 18.88 | 15.93 | 15.79 |

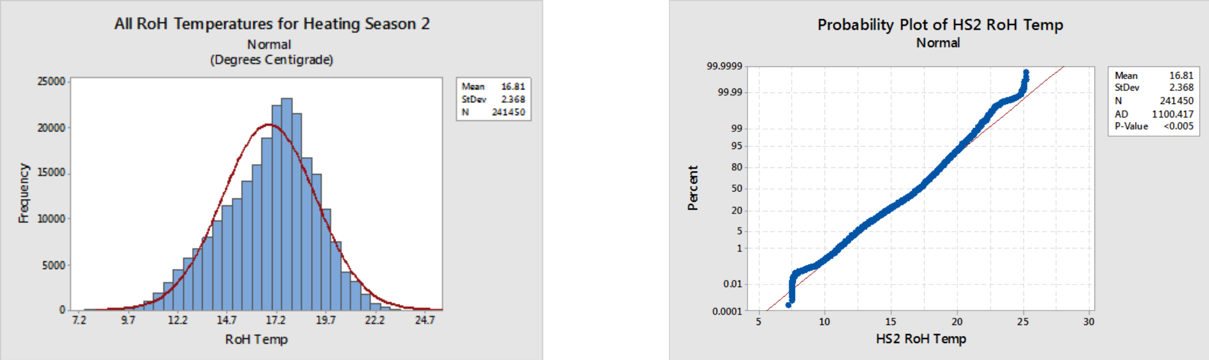


*Figure 15. Histogram and Normality Check on Second Heating Season RoH Temperature.*

## Discussion and Conclusions

The Energy Performance Gap as defined in this paper relates to the over or under consumption of actual household energy use in proportion to the normative model. The gap between the modelled energy for space heating and that used in practice has been identified as being a root cause of the divergence for less thermally efficient housing due, in part, to the limited references to electrical use that are required in EU building energy rating models and from studies working from homeowners utility bills.

The assumptions in the Irish model of the heating schedule and the rest-of-home temperature have been challenged by analysing real time sensor records to investigate possible causes behind the gap in heating energy usage. The DEAP calculation method assumes a heating schedule of 56 hours each week from the 1st October to the 31st May. For the SERVE monitored houses, the actual heating schedule analysis was approached from two angles: firstly from 14 houses with data covering most months of both heating seasons, showing that the heating schedule was between 13 % (cold year) and 32 % (warm year) below the DEAP assumption, on average. Secondly, from a sample of up to twenty houses that had high availability of data for a particular calendar month (but not necessarily consecutive months), resulted in an average heating schedule of 43 hours per week, which is 23 % less than the DEAP assumption.

The rest-of-home bedroom temperatures are still under analysis, but most profiles show that bedroom temperatures rise and fall in line with the outdoor temperature and by varying degrees. Few houses maintained a near constant bedroom temperature over the heating season. Early indications are that a mean temperature of 17 °C was achieved, on average, but, while more research is required on the second heating season's data, the 2012 to 2013 period was much cooler than the previous year so it would be expected that the mean rest-of-home temperature would be even less than 17 °C.

The next steps of the research will be:

- To complete the foregoing temperature analysis and to verify secondary heating usage.
- To gauge the effects of the reduced RoH temperature in DEAP.
- Consolidate the three main research findings with connected research in Ireland along with peer reviews by relevant experts.
- To engage with Sustainable Energy Authority of Ireland to present the findings from this research.

Future work may include:

- Refinement of the rest-of-home heating schedule using the six 15-minute datasets to enable a closer approximation of the start and end times of the heating systems.
- Consideration of an on-line add-on tool to supplement the DEAP calculations to allow more accurate household energy consumption assessments.

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