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Recorded energy consumption of nZEB dwellings – and corresponding interior temperatures.

Initial results from the Irish nZEB101 project.

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ABSTRACT: Ireland is mandating the unprecedented mass market deployment of low-energy dwellings via the near Zero Energy Buildings (nZEB) standard, from 1 January 2021 due to the EU wide Energy Performance of Buildings Directive (EPBD). This is among the first academic papers to provide recorded energy and temperature data for nZEB compliant dwellings in Ireland. It reports on initial results of the www.nZEB101.ie Post Occupancy Evaluation project, the objective of which is to uncover key nZEB design and operations lessons, to aid the next iteration of the country's building regulations. This paper reports on the analysis of winter temperatures and the energy consumption of 17 nZEB compliant dwellings, each of which have been monitored for at least a 12 month period. While analysis of further properties is needed to further validate the findings, key findings to date include significantly higher than expected interior temperatures and energy consumption, and a usage profile which is significantly different from the assumptions in the DEAP National energy rating software.

1. INTRODUCTION

The near Zero Energy Building Standard (nZEB) is required for all new dwellings which will be constructed in the European Union from 2020 [1]. However, with little track record in Ireland for building such low energy dwellings, objective information about how these dwellings will perform is required. This is the first academic paper to provide recorded energy and temperature data for nZEB compliant dwellings in Ireland.

Building on an established Post-Occupancy Evaluation (POE) monitoring project of low-energy dwellings which has been running for over three years, the nZEB101 project [2] is set to uncover the key nZEB design and operations lessons as the Republic of Ireland embarks on the construction of 550,000 of these low-energy buildings by 2040 [3].

Analysis of initial data indicates that

1. Interior temperatures are significantly higher in nZEB dwellings compared with those recorded in previous POE publications, e.g. [4].
2. Interior temperatures are higher than the assumed set temperatures in the national Building Energy Rating (BER) software during the winter period [5].
3. The temperature profile has changed with the living room and Rest of Dwelling (RoD)

temperatures more constant and similar than dwellings built to previous building regulations.

4. The regulated load energy consumption is higher than the BER predicted value the majority of the monitored dwellings – in some cases significantly so. Interior temperatures in the monitored nZEB dwellings are also higher than assumed in the BER software.

These findings are contrary to a recent evaluation of Irish dwellings which had undergone energy retrofit, which found that the DEAP software overestimated both the heating periods and interior temperatures of the pre-nZEB dwellings [6].

The findings are based on a sample of 1/6 of the dwellings which are planned to be monitored by the nZEB101 project.

However, the main finding to date based on the initial POE data is that the nZEB compliant dwellings demonstrate a disparity with the assumptions inherent in the National energy rating software.

2. METHOD

The nZEB101 project is undertaking an extensive Post Occupancy Analysis (POA) of over 100 dwellings which comply with the nZEB regulations. In order to comply with nZEB in Ireland, the buildings need to demonstrate an Energy Performance Coefficient of 0.3

and Carbon Performance Coefficient of 0.35, i.e. reductions of 70% and 65% in energy and carbon emissions respectively compared to a reference building built in 1985 [5].

Data is recorded on the overall energy consumption and the heating energy consumption for all dwellings (1 hour data) for a period of at least one year. In addition, there is five-minute data on the Indoor Environmental Quality (IEQ) parameters of air temperature, relative humidity and carbon dioxide. A subset of the dwellings (table 1) is considered here for the energy analysis and comprises.

- new and retrofit
- detached, semi-detached and terraced
- timber frame and block built and
- private and social housing

As can be seen, three of the new properties are of the same typology and are on the same site ("site I"), and four of the renovated properties are also co-located and of the same typology (site "K"). The majority of the new properties were constructed to the Passive House (PH) standard [7], and have Mechanical Heat Recovery and Ventilation (MVHR) systems for ventilation and all have triple glazed windows apart from nZEB6 which has double glazed fenestration.

Table 1: Selection of monitored nZEB101 dwellings

Dwelling id	New/Renovate	Site	Building type	Construction Concrete/TF	Completed Year	Ventilation	Airtightness (n50/q50)
nZEB1	New	I	Semi-d, 2 stry	Timber Frame	2016	MVHR	0.4
nZEB2	New	J	Det, bungalow	Timber frame	2011	MVHR	0.54
nZEB3	New	L	Det, 2 Stry	Block	2005	MVHR	1
nZEB4	New	N	Det, 2 Stry	Block	2015	MVHR	0.50
nZEB5	New	P	Det, 2 Stry	Timber Frame	2011	MVHR	0.5
nZEB6	Renovate	O	Det, bungalow	Block	2016	Nat Vent	n/a
nZEB7	New	I	Semi-d, 2 storey	Timber Frame	2017	MVHR	0.3
nZEB8	New	I	Semi-d, 2 storey	Timber Frame	2017	MVHR	0.3
nZEB23	Renovate	K	Terraced 1 Storey	Block	2018	DCV	5
nZEB25	Renovate	K	Semi-d, 1 storey	Block	2018	DCV	4.12
nZEB26	Renovate	K	Semi-d, 1 storey	Block	2018	DCV	4.8
nZEB27	Renovate	K	Terraced 1 Storey	Block	2018	DCV	4.8

The majority of the dwellings which have undergone a Deep Energy Retrofit (DER) have Demand Controlled Ventilation (DCV). nZEB6 is a property which was constructed as a low-energy dwelling, with natural ventilation, and while it does not meet the current Irish definition of nZEB, it meets the indicative nZEB definition of regulated load primary energy consumption of less than 45 kWh/m²/a, and is included for comparative reasons [8].

Details of the recorded operational performance of the A-rated buildings, including indoor temperatures over the 2019/20 Winter period as defined by Met Éireann (December, January and February) and regulated load energy consumption which has been recorded over a period of at least one year per property have been provided (Table 2). The regulated load is that

as defined in the Dwelling Energy Assessment Procedure (DEAP) [5] and includes the energy to service the building i.e. Domestic Hot Water (DHW), space heating, fixed lighting and ventilation/pumps.

Given the significantly higher than expected interior temperatures identified in table 2, further, deeper analysis of interior temperatures across the homogeneous sample of nine of the DER properties has been carried out (Figs 2 and 3) and discussed below.

The DER scheme comprises 12 x 1 bed 30.77 m² social house dwellings (Fig 1), located in Wexford town, County Wexford, Ireland, which underwent the DER in 2018. The houses were originally built in the 1970s and house Wexford County Council local authority tenants, typically pensioners.

Prior to the upgrade, the dwellings had issues with inadequate ventilation and thermal bridging resulting in damp patches and mould on interior surfaces. The dwellings ranged from the second poorest Building Energy Rating (BER) rating of F (with a regulated load of 403 kWh/m²/a), to the worst BER (G), with the poorest performing dwelling consuming a regulated load of 1158 kWh/m²/a – as per the BER certificate.

Following the upgrade, the dwellings all are designed to operate in the BER category of A, with the majority having a BER of A2 (25 to 50 kWh/m²/a). The primary heating system is an electric Heat Pump (HP), and one of the dwellings (nZEB 27) also uses a Solid Fuel (SF) open fire with back boiler.



Fig 1 College View, Wexford town, County Wexford, Ireland – pre Retrofit

3. RESULTS

3.1 Overview

Table 2 gives the specific regulated load energy consumption, both in terms of the BER band rating and the specific primary energy consumption in kWh/m²/a. It also gives the recorded specific primary energy consumption, and the recorded average dwelling temperature during the winter (in degrees Celsius).

Table 2: Recorded Energy Consumption Vs Predicted

Dwelling id	Heating System	BER			Actual Reg Load Cons (kWh/m ² /a)	Equiv BER Rating	Ave Dwelling Temp (Winter)
		Rating	Size (m ²)	(kWh/m ² /a)			
nZEB1	HP	A1	102	24.1	40.6	A2	20.1
nZEB2	HP	A3	182	61.6	52.6	A3	21.2
nZEB3	HP	A3	378	61.7	51.6	A3	21.8
nZEB4	HP	A1	285	23.7	26.3	A2	20.8
nZEB5	Gas	A3	271	56.7	72.8	A3	21.8
nZEB6	HP	A3	170	63.0	47.5	A2	18.9
nZEB7	HP	A1	102	24.4	52	A3	21.8
nZEB8	HP	A1	102	24.4	57	A3	22.3
nZEB23	HP	A2	31	47.4	165	C1	21.3
nZEB25	HP	A2	31	36.9	158	C1	21.5
nZEB26	HP	A2	31	36.2	267	D2	24.3
nZEB27	HP & SF	A3	31	65.7	181	C2	22.3

3.2 Energy Consumption

The buildings which exceed the expected energy consumption BER rating band are highlighted in orange in Table 2, and those which operated within or below the expected energy consumption band are highlighted in green.

For four of the dwellings (nZEB2, nZEB3, nZEB5 and nZEB6) the predicted regulated load matches or is below that expected by the Building Energy Rating software. In the case of nZEB4, while the BER A1 band was below the recorded regulated load energy consumption band (A2), the predicted regulated load was very close to the recorded regulated load (23.7 versus 26.3 kWh/m²/a). In the case of nZEB5, the recorded gas consumption (which is used for domestic hot water and space heating in addition to cooking) was being used to determine the regulated load. The dwelling significantly exceeded the expected consumption, and on further investigation it was found that a cookery school for children was being run as a home business, resulting in significantly higher than expected gas consumption.

The recorded performance does not match the predicted specific regulated load for the majority of the dwellings (eight of the 12). For nZEB 1, 7 and 8, the dwellings are on the same site, and were constructed to the Passive House (PH) standard with all having identical construction and heating systems. All three dwellings exceed the predicted Regulated load by approximately twice.

Similarly, in the case of the retrofit dwellings nZEB 23, 25, 26 and 27, all exceed the BER expected energy consumption, typically by a factor in excess of three, and in one case (nZEB 26) by a factor in excess of 7. These are the DER houses in Wexford – see Fig 1. The energy consumption was recorded using clamp on Loop energy meters, and were verified against data collected directly from the Daikin HPs.

Recognising that the regulated load (whilst also comprising fixed lighting and ventilation loads) is predominantly determined by the DHW and space heating loads, a focus was put on the interior temperatures, to determine if the dwelling temperatures matched the levels expected by the Dwelling Energy Assessment Procedure (DEAP)

software which is used to determine the BER and are reported on below.

3.3 Interior Temperatures

The Dwelling Energy Assessment Procedure (DEAP) software which produces the BER assumes that the heating system has a set temperature of 21°C in the living room, and 18°C in all other rooms for two hours in the morning and six hours in the evening. This equates to an average temperature of 18.9°C for eight hours of the day for a typical dwelling, and an unspecified (but assumed lower) temperature for the remaining period. Given that the heating is only expected to be on for one third of the 24 hour period, the overall average dwelling temperature during the winter is expected to be below the 18.9°C.

No nZEB dwelling presented in Table 2 records a temperature below 18.9°C, with nZEB6's *average* temperature at 18.9°, for the 24-hour period, indicating that the temperature during the 8 hour heating period would also be in excess of the DEAP assumptions. So, for all the DER nZEB dwellings analysed, temperatures are higher than expected.

The interior temperatures were compared with a sample of dwellings built to the pre-nZEB standard, it was found that the nZEB temperatures were higher [4]. Of particular note are nZEB 7 and nZEB 8, both of which exceed the energy consumption indicated by the BER rating by approximately 100% and which were also found to have higher than expected living room and bedroom temperatures [9]. As can be seen from table 2, the 24 hour interior temperatures are significantly higher than expected by the BER.

This indicates that there may be an element of “comfort taking”, i.e. the superior thermal performance of the nZEB dwellings is perhaps being used to increase thermal comfort rather than reduce energy consumption.

3.4 Temperature profiles – retrofit dwellings

Given the higher-than-expected overall temperatures, further investigation has been carried out across a sample of 9 of the homogeneous DER monitored dwellings which are located on the same site in County Wexford. This analysis was carried out to determine the interior temperatures:

1. For the eight-hour period heating period.
2. Outside of the heating period.

It was found that the temperatures were significantly different from those expected during the heating periods, and that the temperatures remained high outside of the heating period. See Fig 3 and Fig 4.

The red lines between 5 PM and 11 PM and between 7 AM and 9 AM indicate the expected

temperatures (i.e. 21°C in the living room, and 18°C in the bedroom). For the periods 9 AM to 5 PM and 11 PM to 7 AM, the heating is assumed not to be operational, with the interior temperatures expected to decline over those periods.

Box plots are used to represent the distribution of the dataset. In the box plots, numerical data is divided into quartiles, and a box is drawn between the first and third quartiles. The middle line of the box represents the median or middle value. The median divides the data set into a bottom half and a top half. The bottom line of the box represents the median of the bottom half or 1st quartile. The top line of the box represents the median of the top half or 3rd quartile. The whiskers (vertical lines) extend from the ends of the box to the minimum value and maximum value.

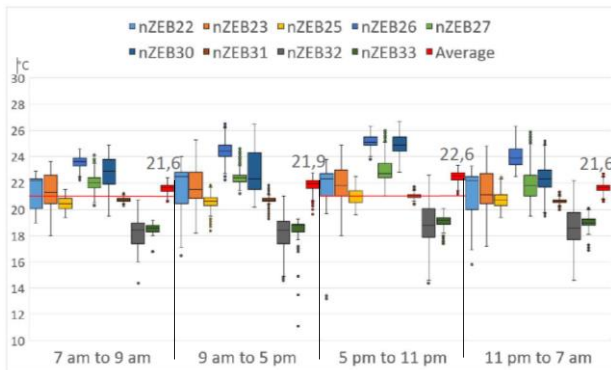


Fig 2 Winter Living room temperatures

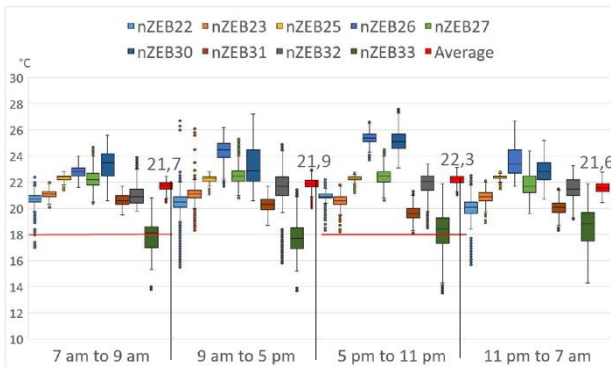


Fig 3 Winter Bedroom temperatures

The box plots give the range of temperatures for each dwelling for the living room (Fig 2) and bedroom (Fig 3). Each dwelling is represented by a box plot in a different colour and the box plots for the average values for the nine dwellings for each of the four time periods (two heating periods, and two non-heating periods) are presented in the red box plots seen on the right of each of the four time periods. The numbers above the average box plots give the overall mean

temperatures experienced for each of the four time periods.

3.5 Living room temperatures

Fig 2 indicates that median living room nZEB interior temperatures are higher than those expected by the energy rating software, for all of the properties apart from nZEB 32, and nZEB 33.

The average temperatures for the nine dwellings over the period 5 PM to 11 PM, continuously exceed the set temperature of 21°C and exceeds it for more than 75% of the time for the period 7 AM to 9 AM. In some cases the temperatures are significantly higher than those expected. For example NZEB 26 and nZEB 30 have median temperatures of 25°C with minimum temperatures in excess of 24°C and 23°C respectively and maximum temperatures of 26°C and 27°C between 5 PM and 11 PM.

Outside of the heating periods, again apart from nZEB 32 and nZEB 33 (which are seen to have the lowest temperatures), the majority of the dwellings continue to exceed 21°C outside of the heating periods. This is a significant finding and reflects high levels of occupancy during the day and a desire for continuous heating, even during the period 11 PM to 7 AM.

The mean temperature ranges between 21.6°C and 22.6°C over the 24 hour period, with relatively stable temperatures experienced by the majority of the properties.

3.6 Bedroom Temperatures

One of the most significant findings for the interior temperatures is that those in the bedrooms are much higher than assumed (Fig 3). The mean temperatures are significantly higher than the 18°C expected, ranging between 21.6°C and 22.3°C, irrespective of the heating/non-heating period.

While the living room temperature is expected to be 21°C during the heating period, the bedroom temperature is expected to be only 18°C during the heating period. Therefore the energy consumption required to maintain the temperatures circa 4°C higher than expected (at a median of c. 22°C) is significantly higher than that expected by the DEAP software.

3.7 Impact of Higher Than Expected Temperatures

The higher-than-expected temperatures will have a significant impact on the energy consumption for the buildings.

For example, in the case of nZEB 26, the average temperature over the winter period is 24.3°C, rather than the expected 19.14°C during the heating period for the individual dwelling, a difference of 5.16°C. The fabric heat loss for the dwelling is calculated at 73 W

per Kelvin by the DEAP software. Therefore to maintain the higher temperatures, $73 \times 5.16^\circ\text{C}$ (or 377 W) is required. Assuming an eight hour heating period (rather than the 24 hour period over which the average temperatures actually have been recorded), over 3 kWh extra energy is required per day, for the 8 hour heating period. Over the winter period alone, this would require an additional to 275 kWh of heating, equivalent to 572 kWh of primary energy (conversion factor 2.08), for the eight-hour period. The DEAP software assumes no energy will be expended on heating for the other two thirds of the day. However, in order to increase the temperature from 19.14°C to the 24.3°C (rather than from the lower yet undefined temperatures outside the heating period, a conservative estimate of 1716 kWh would be required (i.e. multiplying the 572 kWh by three) in order to maintain the building at the recorded temperature for the winter period alone.

Dividing this by the 31 m^2 shows that a (very conservatively estimated) extra specific energy consumption of 55 kWh/m^2 is required to maintain the higher interior temperatures, for the three months of the winter. In order to heat the building for the year an estimate in excess of $100 \text{ kWh/m}^2/\text{a}$ would not seem unreasonable.

Table 2 shows that $245 \text{ kWh/m}^2/\text{a}$ was consumed compared with an expected $36.2 \text{ kWh/m}^2/\text{a}$. The calculations above show the considerable impact that the higher-than-expected interior temperatures had during the analysed winter period alone (c. 50% of the extra primary energy demand).

4. DISCUSSION

This paper has provided initial insights based on the recorded energy consumption of near Zero Energy Building (nZEB) dwellings, in advance of the standard being required for all buildings in the Republic of Ireland from January 2021. The analysis will be augmented as data from more dwellings become available via the nZEB101 project.

The main findings from the analysis:

1. The majority (75%) of the buildings are consuming more energy than predicted by the DEAP software.
2. For the A rated DER dwellings, the energy consumption ranged between 3 and 7 times higher than expected ($158 - 267 \text{ kWh/m}^2/\text{a}$).
3. Recorded interior temperatures are considerably higher than the 18.9°C (for an eight-hour periods) expected by the DEAP software, with 24 hr average temperatures ranging from 18.9°C to 24.3°C over the winter period (Table 2).

4. Analysis of nine dwellings which underwent a deep energy retrofit indicate that the higher interior temperatures are maintained throughout the 24-hour period
5. The bedroom temperatures were on average between 3.7°C and 4.3°C in excess of the 18°C assumed by DEAP.
6. The DEAP - assumed two-hour heating period in the morning and six heating period in the evening were not typical for the buildings monitored.

When the winter interior temperatures of nZEB compliant Passive Houses were compared with a sample of dwellings built to the pre-nZEB standard, it was found that the nZEB temperatures were higher than the dwellings constructed to the previous standards, and also higher than expected by the energy rating software [4], [9]. This indicated that there may be an element of “comfort taking”, i.e. the superior thermal performance of the dwellings is perhaps being used to increase thermal comfort rather than reduce energy consumption. It should also be remembered that a number of the nZEB dwellings monitored as part of the nZEB101 project were built to the Passive House standard, and this may also influence the interior temperatures, as the PH set temperature is assumed to be 20°C for 24 hours a day, which is nearer to the average temperatures measured. Also, higher-than-expected energy consumption and temperatures have been reported in the literature, especially in regard to the rebound effect associated with retrofit dwellings e.g. [10], [11].

On the other hand, the Hunter et al. study [6] of BER C & B Irish retrofit dwellings was conducted on data gathered over the 2011/12 and 2012/13 heating seasons found that DEAP over-estimated heating schedules and room temperatures by up to 37% and 1°C respectively. This is contrary to what was found for the new build and DER Wexford properties would be expected under the rebound effect. It may be explained by the fact that the earlier monitoring coincided with an economic recession during which oil prices were high potentially affecting homeowners’ heating practices. A recent paper [12] by Dennehy et al. found that the economic recession was principally responsible for the sharp fall in residential space-heating energy demand in Ireland between 2007 and 2012, rather than the energy retrofit measures.

Given that economic buoyancy was being experienced in Ireland over the 2019/2020 winter period, this may be a contributing factor to the higher than expected interior temperatures and energy consumption.

Equally, the reason for the higher than expected energy consumption and temperatures may be as a result of occupants concern with heating costs given that they are significantly lower than normal in the PH & nZEB dwellings or for technical reasons e.g. if the Co-Efficient of Performance of the HP did not match that expected. Band C & B dwellings are harder to heat compared to band A, so underheating would be more prevalent for such dwellings as band A are easier to keep warm.

5. CONCLUSION

The potential reasons for the higher than expected energy consumption and temperatures presented is beyond the scope of this paper.

Further monitoring results are required to draw definitive conclusions e.g. with respect to the actual Vs assumed interior temperatures for the DEAP defined heating and non-heating periods, and the actual energy consumption versus predicted.

The contribution of the paper is to present the data on the initial sample of the dwellings complying with the Irish nZEB standard.

While the initial indications are that the heating periods and interior temperatures which were assumed 35 years ago based on the dwellings of the day may need to be revised, it is noted that the sample size of the dwellings is small, and that a significantly greater sample size will be reported on as part of the ongoing nZEB101 project.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

- [1] Anon. Nearly zero-energy buildings. Energy - European Commission 2014.
<https://ec.europa.eu/energy/en/topics/energy-efficiency/energy-performance-of-buildings/nearly-zero-energy-buildings> (accessed September 30, 2019).
- [2] nZEB101 n.d. <http://www.nzeb101.ie/> (accessed September 26, 2019).
- [3] Anon. National Development Plan 2018 - 2027 2018.
- [4] COLCLOUGH S, GRIFFITHS P, HEWITT NJ. Winter performance of certified passive houses In a Temperate Maritime Climate – nZEB Compliant?, Jul 31 to Aug 3 2017a.
- [5] Anon. DEAP 4.2.0 Software. Sustainable Energy Authority Of Ireland n.d.
<https://www.seai.ie/home-energy/building-energy-rating-ber/support-for-ber-assessors/domestic-ber-resources/deap4-software/> (accessed May 12, 2020).
- [6] Hunter G, Hoyne S, Noonan L. Evaluation of the Space Heating Calculations within the Irish Dwelling Energy Assessment Procedure Using Sensor Measurements from Residential Homes. *Energy Procedia* 2017;111:181–94.
<https://doi.org/10.1016/j.egypro.2017.03.020>.
- [7] Anon. What is a Passive House? [] n.d.
https://passipedia.org/basics/what_is_a_passive_house (accessed March 11, 2019).
- [8] Anon. Department of Environment C and LG. Towards Nearly Zero Energy Buildings in Ireland, Planning for 2020 and Beyond. Dublin: Department of Environment, Community and Local Government; 2012.
- [9] Colclough S, Kinnane O, Hewitt N, Griffiths P. Investigation of nZEB social housing built to the Passive House standard. *Energy and Buildings* 2018;179:344–59.
<https://doi.org/10.1016/j.enbuild.2018.06.069>.
- [10] Gillingham K, Rapson D, Wagner G. The Rebound Effect and Energy Efficiency Policy. *Rev Environ Econ Policy* 2016;10:68–88.
<https://doi.org/10.1093/reep/rev017>.
- [11] Galvin R. Making the ‘rebound effect’ more useful for performance evaluation of thermal retrofits of existing homes: Defining the ‘energy savings deficit’ and the ‘energy performance gap.’ *Energy and Buildings* 2014;69:515–24.
<https://doi.org/10.1016/j.enbuild.2013.11.004>.
- [12] Dennehy ER, Dineen D, Rogan F, Ó Gallachóir BP. Recession or retrofit: An ex-post evaluation of Irish residential space heating trends. *Energy and Buildings* 2019;205:109474.
<https://doi.org/10.1016/j.enbuild.2019.109474>.