Life-cycle cost analysis of retrofit scenarios for a UK residential dwelling

Salem, Radwa, Bahadori-Jahromi, Ali ORCID logoORCID: https://orcid.org/0000-0003-0405-7146, Mylona, Anastasia, Godfrey, Paulina and Cook, Darren (2019) Life-cycle cost analysis of retrofit scenarios for a UK residential dwelling. Engineering Sustainability, 173 (2). pp. 57-72. ISSN 1478-4629

http://dx.doi.org/10.1680/jensu.18.00055

This is the Accepted Version of the final output.

UWL repository link: https://repository.uwl.ac.uk/id/eprint/6040/

Accepted manuscript

As a service to our authors and readers, we are putting peer-reviewed accepted manuscripts (AM) online, in the Ahead of Print section of each journal web page, shortly after acceptance.

Disclaimer

The AM is yet to be copyedited and formatted in journal house style but can still be read and referenced by quoting its unique reference number, the digital object identifier (DOI). Once the AM has been typeset, an ‘uncorrected proof’ PDF will replace the ‘accepted manuscript’ PDF. These formatted articles may still be corrected by the authors. During the Production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal relate to these versions also.

Version of record

The final edited article will be published in PDF and HTML and will contain all author corrections and is considered the version of record. Authors wishing to reference an article published Ahead of Print should quote its DOI. When an issue becomes available, queuing Ahead of Print articles will move to that issue’s Table of Contents. When the article is published in a journal issue, the full reference should be cited in addition to the DOI.

Accepted manuscript
doi: 10.1680/jensu.18.00055

Submitted: 11 November 2018

Published online in 'accepted manuscript' format: 26 April 2019

Manuscript title: Life Cycle Cost Analysis of Retrofit Scenarios for a UK Residential Dwelling

Authors: Radwa Salem[1], Ali Bahadori-Jahromi[1], Anastasia Mylona[2], Paulina Godfrey[3], Darren Cook[3]

Affiliations: [1]Department of Civil Engineering and Built Environment, School of Computing and Engineering, University of West London, London W5 5RF, UK. [2]The Chartered Institution of Building Services Engineers (CIBSE), London SW12 9BS, UK. [3]Energy and Environment, Engineering Operations EMEA, Hilton, Maple Court, Reeds Crescent, Watford WD24 4QQ, UK.

Corresponding author: Ali Bahadori-Jahromi, Department of Civil Engineering and Built Environment, School of Computing and Engineering, University of West London, London W5 5RF, UK. Tel.: 07867804039

E-mail: radwa.salem@uwl.ac.uk

Accepted manuscript
doi: 10.1680/jensu.18.00055

Abstract

The UK government is committed to reducing carbon emission levels by 80%, comparative to the 1990 baseline, by 2050. “Nearly Zero Energy Buildings” (nZEBs) were introduced by the ‘Energy Performance Building Directive’ (EPBD) [recast] in 2010 as a realistic solution to the intrinsic environmental debt associated with most existing buildings. This paper aims to carry out a life cycle cost analysis (LCCA) to identify what is a cost-optimal level and how best to achieve this by examining and focussing on the exploration of realistically applicable energy efficient measures and retrofit scenarios for a typical UK dwelling. A sensitivity analysis is used to identify uncertainty and provide the expected economic benefits and losses of the applied scenarios over their respective lifetimes. It was established that the total life cycle costs (LCCs) of all the retrofit scenarios was in fact lower than the baseline scenario (i.e. not retrofitting the property) over the 30 years study period. Furthermore, it was found that the cost-optimal level for the retrofit of a typical UK residential dwelling is 75kWh/m^2/yr; meanwhile, the UK’s current nZEB target stands at 44kWh/m^2/ yr. Meaning there is a gap between the current NZEB target and the calculated cost-optimal level.

Accepted manuscript
doi: 10.1680/jensu.18.00055

Notation

α	discount rate
C	cost (£)
CO_a	annual cost (£)
CO_{INIT}	investment cost (£)
CO_M	maintenance cost (£)
CO_{RNT}	replacement cost (£)
CO_{MSC}	miscellaneous cost (£)
COP	coefficient of performance
D_f	discount factor
i	year
I_{EP}	energy price increase (%)
j	component
R_R	real interest rate
t	time (h)
τ_0	starting year
TC	Calculation period
U	thermal transmittance (W/m2k)
VAL_{fin}	Residual value

Accepted manuscript
doi: 10.1680/jensu.18.00055

1. Introduction

A candid endorsement of the scientific consensus regarding our changing climate has been corroborated in the reports of the 'Intergovernmental Panel on Climate Change' (IPCC) and in the reports of major scientific bodies nationally and internationally. A recent report by the IPCC has highlighted that not limiting rising temperatures to 1.5^{o}C will lead to "rapid, far-reaching and unprecedented changes in all aspects of society" [IPCC 2018]. Mitigation proposals have acknowledged that the building sector plays a vital role in contributing to the ambitious targets set for the transition towards an energy sustainable future. This is derived from statistics stating that the building sector is responsible for 40% of energy consumption across Europe; the domestic sector accounted for a quarter of the total final energy consumption [EC 2017].

Within this framework, on 19th May 2010, a recast 'Energy Performance Building Directive' (EPBD) was introduced within Europe after it had emerged that despite initial efforts of the 2003 EPBD the building sector continued to contribute to 40% of total energy consumption within Europe [Brian 2011; Directive 2010/31/EU (recast)]. It was stated that Member States need to reduce total energy consumption from the building sector and increase usage of renewable energy sources; more specifically this was to be achieved through 'Nearly-Zero Energy Buildings' (nZEBs).

Whilst the recast EPBD has set out a requirement for all new buildings to be nZEBs, including buildings that will undergo refurbishment by 2020, it had only provided a generic definition and no specifications, for instance in terms of specific energy consumption targets, as to how this new concept should be implemented [EC 2012a]. Therefore, an open interpretation has been left for member states. Most importantly, the EPBD stated that, in cases where a cost-benefit analysis of the economic lifecycle of a building is conducted and proven to be negative rather than positive, then the nZEB standard does not need to be applied [Boermans *et al.,* 2011; EC 2012b].

Ideally the concept behind a nZEB is that it is an energy efficient building which employs a renewable and/or microgeneration energy production system. However, in principle, certain traditional buildings can reach the nZEB standard by incorporating only a large renewable energy system. In a literature review study of nZEB definitions, Marszal *et al.,* [2011] highlighted that a majority of the definitions reviewed considered only the incorporation of renewable energy sources, thereby neglecting the inclusion of energy efficiency measures to firstly reduce the energy demand of the building. Consequently, it was concluded that nZEB definitions should place emphasis on improving the energy efficiency of buildings. However, for most dwellings this approach will mean incorporating several energy efficiency measures (EEMs) to reduce the energy demand of the building combined with a small renewable system. This in turn leads to an increase in the capital costs involved in reaching the nZEB standard and further complicates the issue of reaching the standard with 'cost-optimality.' Nair *et al.,* [2010] for instance highlighted that cost can be one of the most significant factors in influencing the energy efficiency investment for existing residential buildings.

Studies have demonstrated that reaching the nZEB standard for residential buildings is technically feasible [Attia 2012; Alessandra *et al.,* 2017; Salem *et al.,* 2018]. Meanwhile,

doi: 10.1680/jensu.18.00055

reaching the nZEB standard whilst considering costs and cost-optimality of the retrofit process and of the individual EEMs remains challenging. Consequently, although there are many studies that focus on the retrofit of buildings to reach the nZEB standard, fewer take into account cost-optimality and reaching a cost-optimal solution. Moreover, many of the definitions that have been or are currently being released throughout the EU only consider energy efficiency, once again neglecting cost-efficiency of the retrofit process [D'agostino *et al.,* 2016].

This paper will therefore examine whether retrofitting a typical UK dwelling to the current nZEB standard is cost-effective for a homeowner with current available standard and cost of technology. The aim is to carry out a life cycle cost analysis (LCCA) to identify what is a cost-optimal level in terms of primary energy consumption (PEC) for a UK residential dwelling. In addition, the paper will investigate how best to achieve this by examining and focussing on the exploration of realistically applicable energy efficient measures (EEMs) and retrofit scenarios. Firstly, Thermal Analysis Simulation software (Tas, Edsl) will be utilised to ensure the retrofit scenarios meet the nZEB standard's energy performance targets. The life cycle cost analysis (LCCA) will be carried out by using building life cycle cost software (BLCC) to compute the life cycle costs (LCCs), net savings, and payback period. A sensitivity analysis will be used to identify uncertainty relative to the retrofit scenarios. Finally, the EPBD's cost-optimal range methodology will be employed to select the cost-optimal solution.

2. Literature review

The analysis of various nZEB case studies and conclusions confirm that to successfully retrofit an existing building into a nZEB the following factors or building elements need to be considered; firstly, because building fabric of most existing buildings is outdated and performs poorly, improvement of fabric insulation levels is necessary [Ma and Wang 2012; Attia 2012]. Improvement of the building fabric also refers to improved air tightness that contributes to minimal air leakage. Air tight constructions mean adequate ventilation is necessary to maintain high level of indoor air quality and prevent air leakage and overheating. With very high airtightness levels, mechanical ventilation becomes a requirement [Michael and Chris 2009; EST 2017].

Winter heating and domestic hot water (DHW) is a particularly important consideration for UK homes due to the UK's cold dominant climate. Heating homes in the UK contributes to approximately 40% of emissions and is the main source of energy consumption within homes. [Jokisalo and Kurnitski 2005; Paressa *et al.,* 2015, EST 2018]. Furthermore, improved glazing is a well-recognised way to significantly improve the overall energy efficiency of the building fabric. Without adequate glazing, even an energy efficient heating system, will not work or run economically [Paressa *et al.,* 2015; Alessandra *et al.,* 2017]. Lighting is the third largest contributor to emissions for UK homes. It accounts for 18% of a typical household's electricity demands and therefore if tackled and made efficient, it can have a very positive contribution to lowering consumption and overall emissions [Figueiredo and Martins 2010; EST 2017]. Finally, renewable systems are a vital part of achieving nZEBs as it is a requirement that energy generation within buildings should come mainly from renewables. [Kolokotsa *et al.,* 2010; Alessandra *et al.,* 2017].

Hamdy *et al.,* [2013] presented a multi-stage simulation-based optimisation method to find cost-optimal and nZEB solutions for a single-family house located in Finland. The results demonstrated that a nZEB with a PEC of 70 kWh/m^2/yr is economically feasible and a range of ≥93 and ≤ 103 kWh/m^2/yr is a cost-optimal energy performance level. Furthermore, the sensitivity analysis showed that an optimal implementation of energy retrofit solutions depends on the installed heating/cooling system and the escalation rate of the energy price. A different study identified the cost-optimal range for nZEBs as 140 kWh/m^2/yr and 0.33 W/Km^2 envelope insulation level, including transmission and infiltration losses per unit heated floor area [Kurnitski *et al.,* 2011]. The UK's current nZEB target stands at 44kWh/m^2/ yr for the PEC. Giuseppe [2018] combined EnergyPlus and JEplus to conduct parametric energy simulations on an existing building case study. Once the combination of all cases was established the probabilistic global cost calculations were conducted based on Monte Carlo methods. This proposed probabilistic approach based on Monte Carlo proved to be effective and useful in comparing how affordable certain EEMs were for designers and home owners.

Comparison of various wall, floor, roof insulation levels and two types of windows and mechanical ventilation with heat recovery systems for a reference residential house showed that a reduction of 23-49% in the space heating energy is the optimal range for retrofitting the house [Bryne *et al.,* 2016]. Kalema *et al.,* [2008] evaluated four building tightness levels, three ventilation-heat recovery types, and nine heating systems to select a cost-effective low-energy solution for a residential house. It was found that improving the thermal insulation of the building is the most preferable retrofit solution to lowering the dwelling's heat energy demand.

doi: 10.1680/jensu.18.00055

On the other hand, a comparative analysis for the selection of an alternative residential energy supply system found that a micro-combined heat and power (CHP) system is a practical and cost-effective alternative in comparison to traditional heating systems [Alanne *et al.,* 2007].

Despite perceived long payback periods and high initial capital investment costs it was demonstrated that triple glazed argon filled windows with a small window to wall ratio, and 200 mm thick insulation on the wall with a payback period of 20 years present a cost-optimal solution for an office retrofit [Pikas *et al.,* 2014]. This highlights the importance of carrying out a LCCA to identify which retrofit solutions and EEMs are truly cost-optimal rather than purely rely on the capital investment costs as an indicator of cost-effectiveness. A study conducted in Portugal in the suburbs of Porto on a multifamily building determined that retrofitting to the nZEB standard can be achieved with a payback period of 13.5-15.0 years [Ferreira *et al.,* 2014]. Rodrigues *et al.,* [2015] concluded that the nZEB standard could be achieved for a 19th century masonry building with an 11 year-payback period. Across the literature there is a consensus that the payback period for nZEB residential retrofit is generally 15 years or more.

Kapsalaki *et al.,* [2012] investigated the design of cost-efficient nZEBs in various climates. It was found that the differences between a cost-efficient and inefficient nZEB can be more than three times in terms of initial and total LCCs. Neroutsou and Coxford [2016] investigated whether a deep retrofit of buildings is a better approach in comparison to a retrofit strategy with lower capital costs on an existing Victorian house in London. It was concluded that rising gas prices, low discount rates, and a long study period made the extensive retrofit an economically efficient option. Mc Grath *et al.,* 2013 the operational energy of two case studies pre/post-retrofit and new build. It was concluded that carrying out high-quality retrofit whilst an "intrusive" and "costly" process the results were in favour of this type of retrofit. The retrofitted building outperformed the new-build by 78 kWh/m^2.

Across the UK's building energy sustainability literature, very few studies deal with reaching the nZEB standard and fewer studies have looked at or considered the costs associated with reaching the current standard. Furthermore, no studies have examined whether the UK's current nZEB target, that is stipulated by the government, falls within the EPBD's calculated cost-optimal level requirements. Therefore, based on the review of the literature, the overall objective of this work is to investigate whether reaching the nZEB standard for a typical UK dwelling is economically viable and whether the current nZEB target matches the cost-optimal level that will be calculated within this paper.

3. Methodology

3.1 Case study

The case study building selected for this paper is a four-bedroom detached dwelling located in Bracknell, Berkshire, England. The dwelling is a typical pre-1990 building and the building regulations to which it was built were below today's standards, making it more challenging to retrofit seeing as it may require more energy efficient measures (EEMs) to be incorporated before it is able to reach the nZEB standard. In terms of representation, the English Housing Survey (2017/18) has reported that 35% of the British population live in detached houses, making it the second most common type of residential dwelling, with semi-detached being the most common. This in turn leads to higher capital investment costs. The energy model and results will be carried out on Tas v9.4.4 software [Tas Edsl, 2018]. The files used to complete the model on Tas are the plan views shown in figure 1a and figure 1b show the outcome of the 3D model created on Tas. Table 1 is showing a summary of the modelling and simulation details.

The following process will be followed:

- Building an accurate 3D model on Tas: Tas has both graphic user interface and text-based results viewer which facilitates the copying of text information to other programs like Excel for analysis. The TAS modeller has the capability of identifying and fixing gaps in the space boundaries, incorrectly orientated surfaces and adjacency problems. TAS has the facility to optimise the building environment, energy performance and occupant comfort, all of which aligns with the scope and aims of this work.
- Thermal simulation of the building and plant/system modelling by the TBD and TSD files, respectively.
- Obtain results such as the energy consumption. The total energy consumption value obtained from Tas considers heating, cooling, auxiliary, lighting, domestic hot water (DHW) and is the net of any electrical energy displaced by renewable/microgeneration systems, if applicable. The PEC is the amount of primary energy consumed in order to meet the building’s energy demand (heating, cooling, DHW, lighting, and auxiliaries) and is also the net of any electrical energy displaced by C/CHP generators, if applicable.

- Utilise TasGenOpt v3.1.1 to conduct parametric simulations and generate retrofit packages that meet the stipulated nZEB target. See section 3.3 for more detail on TasGenOpt.
- Perform LCCA using building life cycle cost software (BLCC) to obtain LCCs, net savings, and payback period for all scenarios including the baseline scenario,

Refer to Amaoko-Attah and Bahadori-Jahromi (2014) for detailed description of the modelling process on Tas.

3.2 Energy model and scenarios

Per EPBD guidelines "Framework Regulations for calculating cost-optimal levels of minimum energy performance requirements (No.244/2012)," individual EEMs were selected and then grouped into retrofit packages or sets. These sets are the retrofit scenarios of the dwelling, with one scenario being the existing state of the dwelling. The directive has proposed a 'cost-optimal range'. To identify the cost optimal level, the LCCs of the various retrofit scenarios will be compared to the PEC (kWh/m^2/yr) to create a cost-optimal curve as illustrated in figure 2a. The lowest point along this curve is the cost-optimal retrofit scenario.

Furthermore, annex I of the EPBD states that "the energy performance of a (nZEB) building shall be expressed in a transparent manner and shall include an energy performance indicator and a numeric indicator of primary energy use, …". It also highlighted that whilst member states can use other indicators, they must not neglect setting a specific value for the PEC. Based on this, it has been recommended that the energy performance indicator should be stipulated as "energy needs for heating and cooling" [Kurnitski 2013]. In essence this means that lowering the energy demand of the building is necessary. For this study, the total PEC will be considered on an annual basis. Consequently, the main indicators to be used throughout the study to assess whether the building has reached the nZEB standard will be the PEC and CO_2 emissions. As for the energy consumption although its results will be investigated, it will not act as an indicator seeing as there is no specific requirement in the EU directive (and as a result in any of the currently available nZEB definitions) that require a specific energy consumption of the building. Table 2 is showing a summary of the u-values of the selected scenarios and table 3 is showing a summary of the selected scenarios that meet the nZEB target [EC 2017; Tas 2018].

In order to select individual EEMs and create retrofit scenarios that meet the nZEB target TasGenOpt v3.1.1 was utilised. TasGenOpt is a utility within Tas software that performs parametric simulations. It minimises the number of simulations and time needed to achieve desirable design options (in this case the nZEB standard target values). GenOpt is currently the most utilised optimisation tool across the literature and was first utilised by Wetter and Wright [2004]. Karaguzel [2014] has demonstrated that Genopt can be used to successfully reduce the LCCs of an office building by 28.7% over 25 years whilst reducing the energy consumption by 33.3%.

Similarly, Hasan *et al.,* [2008] minimised the LCCs of a typical detached Finnish house by combining GenOpt and IDA ICE 3.0. The space heating was reduced by 23-49%. For this study, in order to get design solutions that meet the nZEB standard TasGenOpt is utilised to find optimised values for the various design variables such as external wall u-values, glazing width and type etc. that result in lower overall energy consumption than the baseline scenario [E0]. A range is selected for each of those variables as per typical practise within the literature. The range for this study is ±10% from the desired value (nZEB target). As there is no limit to the number of input and output variables with TasGenOpt the retrofit scenarios are easily generated by inputting multiple variable at once. Figure 2b. is showing an example of how TasGenOpt finds the optimum solution for a desired U-value whilst considering the effect on the heating and cooling demand (and thereby consumption) on the building.

3.3 Life cycle cost analysis: calculation and assumptions

The purpose of conducting the LCCA is to be able to analyse which scenario offers the most profit, in terms of lowest LCCs and therefore highest net savings. This is in correspondence with the EPBD guidelines which state that member states are to select design solutions with calculated “cost-optimal levels,” as discussed earlier. However, when selecting the final solution, it is essential that one finds a balance between the ‘cost-optimal’ solution and the ‘near-zero’ solution. Many studies have concluded that cost optimality and reaching the nZEB standard are two fundamentally related concepts within the EPBD [Famuyibo 2012; Ferreira *et al.,* 2013; Paressa *et al.,* 2015; Alessandra *et al.,* 2017]. Therefore, if one were to focus on the selection of only a cost-optimal solution, then a near-zero solution will not be reached, and vice versa.

The evaluation of the global LCCs is carried out according to standard EN 15459-1:2017: the LCCs $LCC_{(\tau)}$ which is referred to starting year τ_0 are calculated by taking the sum of the initial investment costs CO_{INIT} for component j, the annual cost CO_a for year i which is

doi: 10.1680/jensu.18.00055

discounted by the discount factor D_f (and is dependent on the discount rate α), and the residual value VAL_{fin} of component j in year TC at the end of the calculation period is referred to starting year τ_0 [equation 1]. The calculation period is 30 years as recommended by the European Commission Delegated Regulation's guidelines for residential buildings. The residual value refers to the remaining value of a measure or a retrofit scenario until the end of its lifespan. The European Committee for Standardisation (EU CEN) proposes that residual values are calculated by "linearly prorating the initial investment costs." To elaborate, if we take an EEM with a projected useful life of 60 years, with the study period being 30 years, the residual value will be roughly 50% of the initial investment costs of that measure.

$$LCC_{(\tau)} = CO_{INIT} + \left[\sum_{i=1}^{TC} CO_{a(i)}(j) x \left(D\_f_{(i)} - VAL_{fin(\tau_{TC})}(j) \right) \right] \quad (1)$$

The real interest rate R_R is affected by the interest and inflation rate $R_{interest}$, $R_{inflation}$ and is calculated using equation 2. As for the discount rate α it can be calculated using equation 3. Alternatively, for residential retrofit projects such as this it can be obtained from the Office for National Statistics, which recommends that for projects of 0-30 years a 3.5% discount rate should be adopted.

$$R_R = \frac{R_{interest} - R_{inflation}}{1 + \frac{R_{inflation}}{100}} \quad (2)$$

$$\alpha = \left(\frac{1}{1 + \frac{R_R}{100}} \right)^i \quad (3)$$

The net present value, NPV_{TC} is a "multiplying factor that aims to figure the reduction of the value at the end of period of calculation" and is calculated according to equation 4. It is essentially the sum of the cash flows discounted based on the discount rate which will reflect the "cost of money over time" [SCSI 2012]. Because the LCCA includes cash flows and costs taking place at various time periods of the life cycle of the dwelling it is essential that all those costs are converted to their present values. The present value factor therefore allows for the comparison of the calculated costs of LCCA, including the value of projected future costs, based on the current value of the money.

$$NPV_{TC} = \frac{\Delta I_{NIT} + \sum_{i=1}^{TC} \frac{\Delta_{MNT,i}}{(1+\alpha)^i} + \sum_{i=1}^{TC} \frac{\Delta_{RNT,i}}{(1+\alpha)^i} + \sum_{i=1}^{TC} \frac{\Delta_{MSC,i}}{(1+\alpha)^i}}{\sum_{i=1}^{TC} \frac{\Delta_{ELEC,i} x (1+i_e)^i}{(1+\alpha)^i} + \sum_{i=1}^{TC} \frac{\Delta_{GAS,i} x (1+i_g)^i}{(1+\alpha)^i}} \quad (4)$$

For this work the NPV is split into costs and savings that result from the initial investment (discounted to the time of investment). The NPV is calculated for each scenario and compared to the base-case. The NPV is therefore calculated by summing the (Δ_{INIT}) investment cost; replacement and maintenance costs ($\Delta_{M/RNT}$); miscellaneous costs Δ_{MSC}; in addition to the cost of electricity and gas consumption multiplied by the real energy price increase I_{EP} (for gas and electricity) for year i. The energy price increase rate I_{EP} differs from the inflation rate and is therefore calculated using equation 5 where R_{ep} refers to the expected rise in electricity and gas prices which equals 1.60% i_e and 0.70% i_g, respectively [UK Power 2018a]. Current average cost of gas and electricity for the UK is 3.80 and 14.37 pence/kWh [UK Power 2018b].

doi: 10.1680/jensu.18.00055

$$I_{EP} = \frac{(1+R_{ep})}{R_R + R_{ep}} \left(1 - \frac{1+R_{ep}}{1+R_R} \right)^i \quad (5)$$

Using the above formulae, BLCC software computes the life-cycle costs (in present-value) for the base-case and each alternative retrofit scenario. The software also calculates additional indicators of cost effectiveness such as the net savings and payback period.

4. Results and analysis

4.1 Operational energy use

The various scenarios outlined earlier were implemented in the building on the simulation software Tas and the outcome is shown in table 4. On a purely energy target basis, one can see that scenario E10 is the *optimal* solution. The retrofitting measures incorporated for this scenario resulted in a reduction of the building's annual energy consumption and carbon emissions of 119.59kWh/m^2 (88%) and 43.57Kg/CO_2/m^2 (84.23%), respectively. Whilst scenario E1 and E2 did not meet the standard (as expected), their annual energy consumption is 36.61% and 34.54% lower than the baseline model. The carbon emissions also decreased by 49% for scenario E1 and 46.24% for scenario E2. The reason why scenarios E1 and E2 were included in this study, even though they are not nZEBs, is because the incorporation of those 2 scenarios will provide valuable insight as to whether the nZEB option is in fact more cost efficient despite the expected higher initial investment costs.

4.2 Life cycle cost results

A breakdown of the different costs for each individual scenario has been generated and the sum has been used as the capital investment cost. This was gathered from various databases for UK

2018 energy retrofit of dwellings [innovate UK; Gov; LCF; EST]. Possible grants and/or loans were not taken into consideration for this study, however, schemes such as the Renewable Heat Incentive (RHI) domestic scheme and the Feed-in-Tariff (FIT) scheme were considered, where applicable.

The different elements making up the LCCs for each scenario were sorted into the following categories: 'Energy costs,' 'Maintenance Costs,' 'Replacement Costs,' and 'Initial investment Costs.' Energy costs included fuel and electricity costs (space heating/cooling, DHW heating, lighting, ventilation, and auxiliary). Maintenance and replacement costs involved fabric and systems maintenance and replacements; annual servicing of boilers, CHP, and Mechanical Ventilation (MV) filters; and possible typical servicing and repairs throughout the study period. Miscellaneous costs refer to any investment costs not related to the EEMs; they range from staff fees to planning application costs.

The comparison of the cost contribution of the different elements of the LCCs shown in figure 3 illustrates that for scenarios E3-E10, the capital investment costs, are the most significant cost items over the 30 years calculation period. In comparison to this, the most significant costs in the E0, E1, and E2 scenarios are the energy costs. It is unsurprising to see that the baseline scenario has the highest annual energy costs in comparison to all the other scenarios. The average percentage decrease for the energy related costs between the baseline and the nZEB retrofit scenarios is 61.64%.

Comparing the energy and investment costs highlights an interesting relationship; that is, the higher the investment cost the higher the potential energy performance of the building. In real life applications however, it is simply not possible to just increase investment costs to reach the standard and budgets are usually limited. Therefore, it is necessary to fully explore the cost analysis so that the true benefits may be investigated, rather than just take into consideration surface values such as the initial investment. However, even a small investment still contributes to a reduction in energy costs as demonstrated by scenarios E1 and E2.

Looking at figure 4, one can see that the total LCCs of all the different scenarios is lower than the baseline scenario over the 30 years study period. This means that regardless of which scenario is selected for retrofitting, the selected scenario is in fact cost-effective. In other words, not retrofitting the property is the most expensive option and least profitable over the 30 years calculation period.

The above results demonstrate that looking for a solution with the lowest initial capital investment and shortest payback period is an inadequate indicator of actual cost effectiveness. The payback period is often one of the most significant factors for investors when selecting energy efficient solutions, therefore an investor may be more inclined to select a solution with the shortest payback period even if it is the least profitable solution. Scenarios E8, 9 and 10 had the longest payback period of 20 and 22 years, respectively. Scenarios E1 and E2 had a payback period which is approximately half the time span of the nZEB retrofit scenarios. However, whilst it may seem that the payback period analysis does not justify the high costs, it should be noted that this type of analysis does not represent the true economic viability of the measures.

As mentioned in section 3.1, if a solution was to be selected on a purely energy target basis, then scenario E10 is the optimal scenario. Looking at this now from a purely financial basis, the results above would suggest scenario E1 is the 'cost-optimal solution,' it had the lowest LCCs and thereby generated the highest net savings. However, scenario E1 is not a near-zero solution. Followed by this would therefore be scenario E3, which generated the second highest net savings.

Interestingly, the total LCCs of all retrofit scenarios were within a very close range of £70,000-£73,000. This is because the very small initial investment costs of scenarios E1 and E2 meant that energy costs did not decrease significantly in comparison to scenarios E3-E10. Meanwhile, despite the substantial decrease in energy costs for scenarios E3-E10, the high investment costs meant that the total LCCs remained high. What this indicates is that retrofitting the dwelling to nZEB standard may in fact be as cost-effective as the simple retrofit of the dwelling which does not contribute as much to overall energy savings.

4.3 Sensitivity analysis

4.3.1 Effect of varying discount rate

One of the most significant considerations in LCCA calculations is the discount rate. The results presented above assumed a discount rate of 3.5%. Neroustou (2014) states that the discount rate "represents a quantification of the uncertainty associated with benefits arising from investments." The discount rate therefore has a significant influence on the LCCs and net savings over the study period. Figure 5 demonstrates the effect of increasing the discount rate for the various scenarios. The general trend observed is that as the discount rate value is

doi: 10.1680/jensu.18.00055

increased, all retrofit scenarios become impractical. In more detail, for scenarios E1-E2 and scenarios E3-E10, a discount rate of 8% or more and 5% or more, respectively, means retrofitting is no longer cost effective. A discount rate of 2% or less will mean that scenario E3 surpasses scenario E1, in terms of net savings, and becomes the most cost-effective alternative.

4.3.2 Effect of varying energy/fuel cost

According to UK Power, it has been predicted that there will be a 35% increase in energy demand by 2040, thereby leading to a steadying increase in energy prices. An increase in the fuel price by 5% has meant that all the nZEB retrofit options become more cost effective as shown in figure 6. On the other hand, increasing the energy price meant that scenarios E1 and E2 which are heavily affected by the fuel price, as opposed to the nZEB options, had a significant increase in their energy LCCs. This led to an increase in the overall LCCs which in turn decreased the net savings. Meanwhile, scenarios E3-E10 experienced an increase in net savings as fuel price increased. A decrease in fuel price by 2.5% and more will cause the nZEB scenarios to become uneconomical. This is because the LCCs of the E0 scenario decreases significantly. However, seeing as such fuels are finite resources it is very unlikely that fuel prices will be experiencing any significant reductions compared to current prices. In contrast, an increase of 2.5% or more significantly decrease the economic viability of scenarios E1 and E2. A 5% increase or more means that those two scenarios will no longer be generating any substantial net savings.

doi: 10.1680/jensu.18.00055

4.3.3 Effect of varying study period

From figure 7 it can be seen that a longer study period generates higher overall net savings. The net savings are higher for the nZEB retrofit scenarios in comparison to the scenarios E1 and E2. A study period of 20 years and less means that all nZEB scenarios are no longer cost effective. For the nZEB retrofit scenarios this occurred because even with the substantial reduction in energy costs, the initial investment cost remains too high and cannot be balanced. Meanwhile, a study period of 15 years and less caused scenarios E1 and E2 to become unprofitable, because despite the lower investment costs, the large energy costs eventually led to the total LCCs increase which decreased net savings. Recent statistics have shown that recently homeowners are moving on average 1.8 times over their lifetimes in comparison to 3.6 times prior to 2008 [Finder 2018; BSA 2018]. This means that homes are being re-mortgaged only once every 20 years, with majority of homeowners not moving at all and spending an average of 39 years in the property [Finder 2018; FCA 2018]. Projections estimate that this figure will only increase with rising house prices across the UK. Therefore, for the average UK homeowner a study period of 30 years and more should be considered.

4.3.4 Effect of varying weather data

The scenarios were simulated once more under future climate projections to see the effect of implementing nZEB retrofit under potentially different climatic conditions. The energy costs of the scenarios were therefore recalculated based on the new energy consumption values generated under future weather projections (assuming the initial constant fuel price). The future weather projections investigated are the 'High' scenarios for the 2020s, 2050s, and 2080s weather data sets [Cibse 2018]. Interestingly, figure 8 shows a decline in net savings as future weather projections are simulated for the nZEB scenarios; meanwhile for scenarios E1 and E2 there is a slight increase in the net savings. This is because the projections showed a continuous increase in temperatures over stipulated timelines which led to an increase in the energy consumption. The high levels of insulation and airtightness for the nZEB scenarios meant that the cooling demand increased significantly in comparison to scenarios E1 and E2 which did not include improvement to the building envelope and therefore were not affected in the same way as the nZEB retrofit scenarios.

4.4 Cost-optimal solution

The results obtained provided valuable insight regarding which measures are the most cost-effective relative to their contribution. The following deductions can be obtained from the sets of EEMs above:

Rather than simply increasing the thickness of insulation materials an optimal thickness needs to be determined and selected. This can be seen by looking at the U-values for scenarios E6-E10, which use the same material but had an increase in thickness. This showed that increasing the thickness of material past a certain thickness provided little/no decrease in U-values. Although, several variables were changed within the retrofit package, these findings have been corroborated amongst other studies [Ma and Wang 2012; Alessandra *et al.,* 2017; Salem *et al.,* 2018]. Furthermore, based on the sensitivity analysis results, improving the

doi: 10.1680/jensu.18.00055

building envelope should be carefully selected to ensure that under future climate change the building can maintain its near-zero status.

In terms of cost effectiveness, the solar thermal heating system and high efficiency biomass boilers are the most cost effective at meeting heating and DHW demand whilst having lower initial investment costs and benefiting from their eligibility for the RHI and FIT schemes which further lowers the LCCs. Although Ground/Air source heat pumps are eligible for the RHI scheme, their very high initial investment costs and the lower efficiency, in comparison to the other two measures, mean the investment cost is too high to be justified. Similarly, Moran *et al.,* 2017 conducted a LCCA and a sensitivity analysis on 8 Irish dwellings and concluded that future nZEB buildings should be designed to utilise heating systems with a "low impact on the natural environment, such as a biomass boiler."

To meet all/most of the electricity demand a 4kW PV system is the most suitable option and will allow the nZEB standard to be reached even if other elements are neglected. This will further lower the initial costs. Similarly, the 2kW micro-CHP system can meet and even exceed the annual electricity demand of the dwelling. Furthermore, the CHP system also has the benefit of supplying heat and can meet most of the DHW demand. Nonetheless, it should be noted that nZEBs are intended to be truly energy efficient buildings. Asdrubali *et al.,* (2019) concluded that when longer study periods are considered renewable energy technologies offer a higher reduction of energy consumption and emissions. Therefore, rather than just meeting the near-zero balance, it is important that the energy efficiency of the dwelling overall is improved to lower the demand of the dwelling; as opposed to introducing a large renewable system to

doi: 10.1680/jensu.18.00055

meet the existing high demand. This is also highlighted by Moran *et al.,* 2017 whereby it was found that super-insulated, high air-tight retrofitting offers a better alternative to just adding renewable technology in a temperate oceanic climate. However, issues of overheating under future climatic conditions must be taken into consideration before implementing such an approach [Salem *et al.,* 2019]. The CIBSE adaptive comfort approach places emphasis on designing buildings so that they allow occupants to control their environment, thereby comfort can be achieved [CIBSE 2013 and 2015].

Financially, it is more effective to select double glazing (with a low emissivity coating) rather than triple glazing. Although scenarios with double glazing did not meet the nZEB target for window u-values, overall the space heating demand, energy consumption, and carbon emissions did not vary significantly. Instead, sets with double glazing had lower initial investment costs, total LCCs and shorter payback periods thereby leading to higher investment. Although other studies have demonstrated that triple glazing can form part of a cost-optimal solution, these are typically based in colder climates [Kuusk and Kalamees 2015; Moran *et al.,* 2017].

Mechanical ventilation systems increased investment and LCCs under current and future weather projections. Overall, they contributed very little to the overall energy and cost-efficiency of the dwelling. Adequate insulation combined with natural ventilation performed more effectively under future weather projections. Natural ventilation is typically not a realistic option for nZEB buildings, and this is due to the overall ventilation rate changing as a result of improving the building envelope. However, because the building envelope in this case will not be significantly improved to the required nZEB standard, natural ventilation will now suffice to meet the required ventilation airflow.

As discussed previously, the directive has proposed that the cost-optimal solution is selected based on the comparison of the LCCs of the different combinations of scenarios to the PEC of the dwelling (kWh/m^2/yr). However, prior to comparing the PEC with the LCCs, the nZEB scenarios were altered according to the findings above and their LCCs recalculated. The scenarios were altered because, as discussed previously, the initial criteria for the simulations focussed only on meeting the nZEB target and having lower total energy consumption than the baseline scenario. Whilst this lowered the energy costs, and thereby LCCs, the aim, however, was to look further into the type of EEMs that were compatible with the dwelling in terms of not only energy performance, but also costs based on the above findings and considerations. The alterations were as follows:

- The insulation of scenarios E3-E10 will be changed so that the external wall is 130 mm EPS, the Roof and Ground floor are 95 mm and 80 mm XPS, respectively. Any further increase in thickness increases costs unnecessarily.
- Natural ventilation will be simulated for all scenarios
- Measures which used Ground/Air source heat pumps will be altered so that they use a high efficiency gas boiler.
- All glazing for scenarios E3-10 will be changed to ‘Double Glazing, Argon Filled, Low-e.’

The altered scenarios are now labelled AE3-AE10. The LCCs and primary energy demand of scenarios E0-E10 plus scenarios AE3-AE10 were used to make up the cost-optimal range shown in figure 9. The previous LCC calculations showed that solution E3 was the cost-optimal solution. Correspondingly, the altered solutions also demonstrate that scenario AE3 is the cost-optimal solution as it is the lowest point on the cost-optimal curve. The percentage decrease in investment cost and LCCs between solution E3 and AE3 is 39.12% and 32%, respectively. In general, the altered solutions showed a 35-45% decrease in cost in comparison to the initial scenarios. Whilst this altered solution does not meet all the different targets (e.g. u-values) outlined earlier in table 3, the energy consumption and carbon emissions did not exceed the nZEB goal. Based on this it can also be seen that the cost-optimal level for the retrofit of a typical UK residential dwelling is 75kWh/m^2/yr; meanwhile, the UK's current nZEB target stands at 44kWh/m^2/ yr. Meaning there is a gap between the current NZEB target and the established cost-optimal level. One of the simplest ways to bridge this gap would be to improve the rates for the currently available incentive schemes and possibly introduce new ones to further support the economic feasibility of the nZEB standard.

5. Conclusions

This paper explored a LCCA of various energy efficient and nZEB retrofit scenarios on a typical pre-1990 UK residential dwelling. Areas of focus to retrofit the dwelling were categorised based on a descriptive methodology. A parametric optimisation utility within Tas software was adopted to select the sets of retrofit scenarios.

The following general conclusions can be made about reaching the standard with a focus on cost efficiency, firstly, the building to be retrofitted should be analysed, and its base performance determined to establish areas of focus. Based on this, the next step should be to select the appropriate retrofit scenarios with EEMs applicable to the dwelling. Once this is done the energy performance, including the PEC, of the dwelling for each scenario may then be checked for compliance with selected standard. Subsequently, the economic calculations for each retrofit scenario may then be carried out for the selected study period. The cost-optimal solution may then be selected based on a balance between nZEB targets and the LCCs of the retrofit measures.

The results highlighted that incorporating a renewable/trigeneration system is crucial to achieving the Near-Zero standard. Even with triple glazing and very high levels of insulation the energy consumption and carbon emissions levels would not meet the nZEB standard when simulation trials were being conducted initially. Moreover, incorporating renewables did not have a significant impact on overall cost-effectiveness as illustrated by the lack of difference of the LCCs between scenarios E1 and E2 and the nZEB scenarios.

For this paper it was decided that the most cost-effective solution is the nZEB solution with the lowest LCCs and therefore highest net savings, which was scenario E3 and finally the altered scenario AE3. Scenarios E1 and E2 showed that it is possible to improve the energy efficiency of the dwelling with very low initial investment costs (less than £70/m^2) and still generate net savings. The results showed that with the current prices of EEMs, retrofitting dwellings to reach the nZEB standard may mean the initial investment costs are higher than certain landlords' budget capacity. Therefore, from this point of view it may be more realistic to improve the energy efficiency of the dwelling to some extent now by 40-50 percent, as in the case of scenarios E1 and E2, then as EEMs' application becomes more widespread, leading to lower costs, they can be incorporated in the future.

Retrofitting to improve the building fabric increased the overall investment costs significantly; meanwhile, their contribution to reducing energy consumption and carbon emissions were insignificant in comparison to some of the renewable measures which had similar initial costs. Moreover, the energy consumption and carbon emissions targets were achieved when the building fabric measures were not improved for the altered scenarios. However, this does not mean they should be entirely neglected; as an alternative, building fabric material should be carefully sized and selected to reasonably improve overall u-values whilst keeping costs to a minimum. This also emphasises that to successfully retrofit existing buildings, it will be necessary to redefine the energy performance level of the building fabric to match a realistic cost-effective level, that will also consider the requirements of the investor.

The purpose of conducting the sensitivity analysis is not only to investigate the influence of various fluctuating variables and analyse which of those variables have the greatest impact on net savings, but to also examine under which conditions do the nZEB retrofit scenarios increase in cost-effectiveness. The sensitivity analysis therefore showed that the 'ideal' combination of a discount rate $\leq 3\%$, an increase in fuel price $\geq 5\%$, and a longer ($\geq 30\, years$) calculation/ investment period considered will mean the nZEB retrofit scenarios become more cost-effective for the homeowner. It was interesting to observe that the nZEB retrofit scenarios decreased in cost efficiency as future weather projections were simulated. To counteract this issue, two options are available, one would be to include an energy efficient cooling system as part of the retrofit. On the other hand, the other option would be to exercise cautiousness when improving the building fabric to avoid any overheating because of raised temperatures in the future. Generally, this illustrates the importance of careful planning and designing to retrofit a resilient building that performs up to standard even under potentially different climatic conditions.

Although there was a mismatch between the PEC for the current nZEB target and the cost-optimal solution, the results demonstrated that the nZEB retrofit is still a viable option in comparison to the baseline scenario over the 30 years study period.

Overall, the cost-optimal solution that was selected for this paper was based on net savings over the calculated study period. In real life applications, the cost-optimal solution will largely depend upon the requirements of the investor. However, the same steps of creating several retrofit scenarios and comparing them is essential to reaching the nZEB standard with cost-optimal levels.

References

Alanne K, Salo A, Saari A and Gustafsson SI (2007) Multi-criteria evaluation of residential energy supply systems. *Energy and Buildings* **39**(12): 1218-1226

Attia S (2010) Zero Energy Retrofit Case Study of a chalet in Ain-Sukhna, Egypt. *American Solar Energy Society Conference, 217-222, May 2010, Phoenix, Arizona, USA.*

Amoako-Attah J and B-Jahromi A (2014) Impact of standard construction specification on thermal comfort in UK dwellings. *Advances in Environmental Research* **3**(3): 253-281.

Alessandra S, François G, Josef A, Daniel A, Laura A. (2017). *Solution Sets for Net Zero Energy Buildings*. Berlin, Germany: Wilhelm Ernst & Sohn. p46-86.

Asdrubali F, Ballarini I, Corrado V, Evangelisti L, Grazieschi G and Guattari C (2019) Energy and environmental paybak times for an nZEB retrofit. *Building and Environment* **147**: 461-472

Brian A (2011) *Energy Performance of Building directives.* Available: http://www.bre.co.uk/filelibrary/Scotland/Energy_Performance_of_Buildings_Directive_(EPBD).pdf (accessed 14th September 2018).

Boermans T, Bettgenhäuser K, Hermelink A and Schimschar S (2011) Cost Optimal Building Performance Requirements. Calculation Methodology for Reporting on National Energy Performance Requirements on the Basis of Cost Optimality within the Framework of the EPBD. European Council for an Energy Efficient Economy, Sweden

Bryne A, Bryne G, O'Donnell G and 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

Buildings: European Commission (Ec) (2017) *Buildings.* Available: https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings (accessed 20th September 2018).

Building Societies Association (BSA) (2018) *Mortgage and Housing Statistics.* Available: https://www.bsa.org.uk/statistics/mortgages-housing (accessed 20th September 2018).

Cibse (2018) *Cibse weather data sets.* Cibse, London, UK. Available: https://www.cibse.org/knowledge/cibse-weather-data-sets (accessed 17th September 2018)

D'Agostino D, Zangheri P, Cuniberti B, Paci D and Bertoldi P (2016) *Synthesis Report on the National Plans for Nearly Zero Energy Buildings (nZEBs).* Available online: http://publications.jrc.ec.europa.eu/repository/ bitstream/JRC97408/reqno_jrc97408_online%20nzeb%20report.pdf (accessed 23rd September 2018).

European Parliament and the Council of the European Parliament Directive 2010/31/EU (recast) (2010) Directive 2010/31/EU of the European parliament and of the council of 19 May 2010 on the energy performance of buildings (recast). *Official Journal of the European,* **153**: 18-45.

Edsl Tas (2018) *Thermal Analysis Simulation Software*. Available at http://www.edsl.net/. (accessed 17th September 2018).

European Commission (2012a) Guidelines accompanying the Commission Delegated

Regulation (EU) No. 244/2012 of 16 January 2012, supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings. *Official Journal of the European Union* **115**: 1-28.

European Commission (2012b) Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology framework for calculating cost optimal levels of minimum energy performance requirements for buildings and building elements. *Official Journal of the European Union* **81**:18-36

Famuyibo A (2012) *Reducing life cycle impacts of the existing Irish housing stock*. PhD thesis, Dublin Institute of Technology, Dublin. Ireland.

Ferreira M, Pereira M, Almeida M and Rodrigues A (2013) Cost optimal building renovation with a net zero energy target for the Portuguese single-family building stock built before 1960. *Sustainable Building Conference SB13 proceedings, 3-10, June 2013, Guimaraes, Portugal..*

Ferreira M, Almeida M, Rodrigues A and Silva S (2014) Comparing cost-optimal and net-zero energy targets in building retrofit. *Building Research and Information* **44**: 188-201.

Figueiredo J and Martins J (2010) 'Energy production system management - Renewable energy power supply integration with building automation system.' *Energy Conversion and Management* **51**(6): 1120-1126

Finder (2018) *What are the latest statistics for UK mortgages?* Available:

https://www.finder.com/uk/mortgage-statistics (accessed 27th September 2018).

Financial Conduct Authority (FCA) (2018) *Mortgage Statistics - September 2018*. Available: https://www.fca.org.uk/data/mortgage-statistics (accessed 25th September 2018).

Gov.uk (2019) *English Housing Survey 2017-2018*. Available: https://www.gov.uk/government/statistics/english-housing-survey-2017-to-2018-headline-report. (accessed 1st February 2019)

Di Giuseppe E (2018) A parametric building design tool for assessing energy savings and life cycle costs. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability* **00**: 1-10

Hasan A, Mika V and Siren K (2008) Minimization of life cycle cost of a detached house using combined simulation and optimization. *Energy and Buildings* **48**: 2022–2034.

Hamdy M, Hasan A, Siren K. (2013). A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010. *Energy and Buildings,* vol 56, p189-203.

Intergovernmental Panel on Climate Change (IPCC) (2018) *Global warming of 1.5^{o}C special report*. Available at: http://www.ipcc.ch/report/sr15/. (accessed 27th September 2018).

Jokisalo J and Kurnitski J (2005) *Effect of the thermal inertia and other building and HVAC factors on energy performance and thermal comfort in apartment buildings*. Report B79, Helsinki University of Technology.

Karsten V, Eike M and Markus L (2010) From Low-Energy to Net-Zero Energy Buildings. *Journal of Green Building* **52**(6): p24-36.

Kolokotsa D, Rovas D, Kosmatopoulos E, and Kalaitzakis K (2010) A roadmap towards intelligent net zero- and positive-energy buildings. *Solar Energy* **85**(12): 3067-3084

Kurnitski J, Saari A, Kalamees T, Vuolle M, Niemela J and Tark T (2011) Cost optimal and nearly zero (nZEB) energy performance calculations for residential buildings with REHVA definition for nZEB national implementation. *Energy and Buildings* **43**(11): 3279-3288.

Kapsalaki M, Leal V and Santamouris M (2012) A methodology for economic efficient design of Net Zero Energy Buildings. *Energy and Buildings* **55**: 765-778

Karaguzel OT, Zhang R and Lam KP (2014) Coupling of whole-building energy simulation and multi-dimensional numerical optimization for minimizing the life cycle costs of office buildings. *Building Simulation* **14**(7): 111–121.

Kuusk K and Kalamees T (2015) nZEb retrofit of a concrete large panel apartment building. E*nergy Procedia* **78**: 985-990.

Michael J and Chris S (2009) *A Practical Guide to building Airtight Dwellings.* Available: http://www.zerocarbonhub.org/sites/default/files/resources/reports/A_Practical_Guide_to_Building_Air_Tight_Dwellings_NF16.pdf (accessed 14th September 2018).

Marszal AJ, Heiselberg P, Bourrelle JS, Musall E, Voss K, Sartori I and Napolitano A (2011) Zero Energy Building – A review of definitions and calculation methodologies. *Energy and Buildings* **43**(4): 971-979.

Ma P and Wang LS (2012) Effective heat capacity of interior planar thermal mass (iPTM) subject to periodic heating and cooling. *Energy and Buildings* **47**: 44-52.

Mc Grath T, Nanukuttan S, Owens K, Basheer M and Keig P (2013) Retrofit versus new-build house using life-cycle assessment. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability* **166**(3): 122-137

Moran P, Goggins J, Hajdukiewicz M (2017) Super-insulate or use renewable technology? Life cycle cost, energy and global warming potential analysis pf nZEBs in a temperate oceanic climate. *Energy and Buildings* **139**: 590-607.

Nair G, Gustavsson L and Mahapatra K (2010) Factors influencing energy efficiency investments in existing Swedish residential buildings. *Energy Policy* **37**: 2956-2963.

Neroutsou T (2014) Lifecycle Costing of Low Energy Housing Refurbishment: A case study of a 7-year retrofit in Chester Road, London. *8th Windsor Conference: Counting the Cost of Comfort in a changing world, 10-13 April 2014. Windsor, UK*

Neroutsou T and Coxford B (2016) Lifecycle Costing of Low Energy Housing Refurbishment: A case study of a 7-year retrofit in Chester Road, London. *Energy and Buildings* **128**: 178-189.

Kalema T, Johannesson G, Pylsy P and Hagengran P (2008) Accuracy of energy analysis of buildings: A comparison of a monthly energy balance method and simulation methods in calculating the energy consumption and the effect of thermal mass. *Journal of Building Physics* **32**(2): 101-130.

Office for National Statistics (ONS) (2017) *People, population and community: Housing.* Available: https://www.ons.gov.uk (accessed 26th September 2018)

Pikas E, Thalfeldt M and Kurnitski J (2014). Cost Optimal and nearly zero energy building

doi: 10.1680/jensu.18.00055

solutions for office buildings. *Energy and Buildings Journal* **74**: 30-42.

Paressa L, Thaleia K, Andy D and Regina B (2015) Integrating Life Cycle Energy into the Design of Façade Refurbishment for a Post-War Residential Building in The Netherlands. *Buildings Journal* **5**: 662-649.

Rodrigues F, Parada M, Vicente R, Oliveira R and Alves A (2015) High Energy Efficiency Retrofits in Portugal. *Energy Procedia* **83**: 187-196

Society of Chartered Surveyors Ireland (SCSI) (2012) *Life Cycle Costing*. Available: https://www.scsi.ie (accessed 28th September 2018)

Salem R, Bahadori-Jahromi A, Mylona A, Godfrey P and Cook D (2018) Retrofit of a UK residential property to achieve nearly zero energy building standard. *Advances in Environmental Research* **7**(1): 13-28

UK Power (2018a) *Energy Price Forecast*. Available: https://www.ukpower.co.uk/home_energy/future-gas-electricity-price-forecast (accessed 27th September 2018).

UK Power (2018b) *Gas & Electricity Tariff Prices per kWh.* Available: https://www.ukpower.co.uk/home_energy/tariffs-per-unit-kwh (accessed 26th September 2018).

Wetter M and Wright J (2004) A comparison of deterministic and probabilistic optimization algorithms for non-smooth simulation-based optimization. *Building and Environment* **39**: 989–999.

doi: 10.1680/jensu.18.00055

Table 1. Summary of modelling and simulation details

Construction database	**NCM Construction -v5.2.tcd**
Zone - occupancy levels, people density, lux level	Bedroom - 0.0229 person/m^2, 100 lux Toilet (water closet/WC) - 0.024 person/m^2, 100 lux Food prep/ kitchen- 0.023 person/m^2, 300 lux Bathroom – 0.0187 person/m^2, 150 lux Circulation - 0.016 person/m^2, 100 lux Common area – 0.0196 person/m^2, 100 lux Lounge – 0.0188 person/m^2, 150 lux Dinning – 0.0169 person/m^2, 150 lux
Building Fabric – Calculated area weighted average U-values	Wall – 0.32 W/m^{2}K Floor – 0.57 W/m^{2}K Roof – 0.29 W/m^{2}K Window – 3.45 W/m^{2}K
Cooling	No Cooling system
Heating	Type: conventional boiler system Fuel: natural gas Temperature Set point: 21^{o}C Heating Capacity: 2kW Working Temperature: 50-70^{o}C Heating distribution: Central heating radiators Schedule: October-April 5am-9pm [ONS, 2017]
Domestic Hot Water (DHW)	Type: Gas boiler Temperature: 50^{o}C Average daily consumption: 140 litres per person per day
Ventilation	Type: Passive/Natural Schedule: 8am-10am; 7pm-8pm
Fuel Source	Natural Gas – CO_2 Factor – 0.198 Kg/kWh Grid Electricity - CO_2 Factor – 0.4121 Kg/kWh
Orientation	51.4174° N; 0.7249° W; +0.0 UTC
Air Permeability	6 m^3/h/m^2 @50Pa
System efficiencies	ASHP – COP of 3 GSHP – COP of 3 CHP – 37% elec. efficiency & 47% heat efficiency Biomass Boiler – 85% efficient MVHR -Specific fan power = 0.5 & heat recovery efficiency = 90% SWH – Zero loss collector efficiency = 0.81; heat loss coefficient = 3.9

Weather data	TRY (CIBSE) for London. Includes: Global solar radiation, Relative Humidity, Wind Speed and Wind direction, Dry Bulb Temperature, Diffuse Solar radiation, and Cloud Cover.
Occupancy Profile	Weekday [Mon-Fri]: 6pm-8am Weekend [Sat-Sun]: 24 hrs [ONS, 2017]

doi: 10.1680/jensu.18.00055

Table 2. The nZEB target values and summary of u-values for all scenarios

	Detached House ('Balanced'/nZEB)[1]	E0	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10
External Wall U-value (W/m^2k)	0.15	0.32	0.30	0.32	0.17	0.16	0.15	0.33	0.30	0.16	0.15	0.15
Ground floor U-value (W/m^2k)	0.13	0.57	0.57	0.56	0.15	0.14	0.13	0.13	0.14	0.14	0.12	0.10
Window U-value (W/m^2k)	0.80	3.45	2.93	2.70	0.80	0.95	0.81	0.90	1.12	2.65	2.80	2.32
Roof U-value (W/m^2k)	0.13	0.29	0.27	0.30	0.12	0.15	0.15	0.17	0.15	0.12	0.11	0.11

Accepted manuscript
doi: 10.1680/jensu.18.00055

Table 3. Summary of all the different scenarios selected to undergo simulation and lifecycle cost (LCC) analysis

Scenario	Energy Efficient Measures (EEMs) -NCM constructions database v 5.2.tcd					
	EEM1 (Thermal Insulation)	EEM2 (Ventilation)	EEM3 (Heat/ Domestic Hot Water -DHW)	EEM4 (Lighting)	EEM5 (Glazing)	EEM6 (Renewable/Microgeneration Systems)
E0 (Baseline)	External wall: 85mm mineral wool quilt Roof: 50mm mineral wool quilt Ground floor: 35mm Expanded polystyrene (EPS)	Natural Ventilation	Old gas boiler	Incandescent	Uncoated glass, air filled	N/A
E1 (Energy efficient -but not nZEB)	External wall: 85mm mineral wool quilt Roof: 50mm mineral wool quilt Ground floor: 35mm EPS	Natural Ventilation	Low Temperature Hot Water (LTHW) boiler	Incandescent	Double Glazing, Air filled, Low-e	2kW Solar thermal heating (Flat collectors)
E2 (Energy efficient -but not nZEB)	External wall: 85mm mineral wool quilt Roof: 50mm mineral wool quilt Ground floor: 35mm EPS	Natural Ventilation	High Efficiency gas boiler	Incandescent	Double Glazing, Coated glass, Argon filled	2kW Solar panels [18 panels – 28.8m^2]
E3	External wall: 95mm Rock Wool Roof: 95mm Extruded Polystyrene (XPS) Ground floor: 140mm XPS	Mechanical Ventilation: Natural inlet and mechanical extract	8kW Ground Source heat pump (electric)	Light emitting diode (LED) + Auto Presence detection	Triple Glazing, Argon filled, Low-e	Monocrystalline Solar panels (roof) - 16% efficient 3kW module (with electricity storage)

doi: 10.1680/jensu.18.00055

E4	External wall: 95mm Mineral wool batt Roof: 95mm Mineral wool batt Ground floor: 100mm mineral wool	Mechanical Ventilation with heat recovery (MVHRV)	High Efficiency (gas) Boiler	Compact fluorescent lamp (CFL) + Auto presence detection	Triple Glazing, Air filled, Low-e	Monocrystalline Solar panels (roof) - 20% efficient 4kW module (with electricity storage)
E5	External wall: 120mm Glass wool quilt Roof: 95mm Glass wool Ground floor: 150mm mineral wool	Mechanical Ventilation with energy recovery ventilator	High Efficiency (gas) Boiler	LED	Double Glazing, Argon filled, Low-e	Micro-CHP 2kWe with heat recovery system
E6	External wall: 100mm EPS Roof: 95 mm XPS Ground floor: 60 mm XPS	Mechanical Ventilation with variable refrigerant flow (VRF)	6kW Ground Source Heat pump	Halogen incandescent (with dimmers)	Triple Glazing, Argon filled, uncoated	Monocrystalline Solar panels (roof) - 16% efficient 3kW module
E7	External wall: 120mm EPS Roof: 100mm XPS Ground floor: 70 mm XPS	Mechanical Ventilation: Mechanical inlet and extract	High Efficiency (biomass) Boiler	CFL	Triple Glazing, Air filled, uncoated	Monocrystalline Solar panels (roof) - 20% efficient 4kW module
E8	External wall: 130mm EPS Roof: 120mm XPS Ground floor: 80 mm XPS	Automatic mixed-Mode ventilation	LTHW (gas) Boiler	LED	Triple Glazing, Argon filled, Low-e	Micro-CHP Fuel Cell System– 2kWe
E9	External wall: 160mm EPS Roof: 130mm XPS Ground floor: 90 mm XPS	Mechanical Ventilation with heat recovery (MVHR)	5kW Air Source Heat Pump (ASHP)	LED	Double Glazing, Coated glass, air filled	Monocrystalline Solar panels (roof) - 16% efficient 3kW module (with electricity storage)

E10	External wall: 180mm EPS Roof: 140mm XPS Ground floor: 100 mm XPS	Mechanical Ventilation with VRF	High Efficiency (gas) Boiler	CFL	Double Glazing, Argon filled, low-e	Micro-CHP 2kWe

Table 4. The nZEB target values and summary of results for all scenarios.

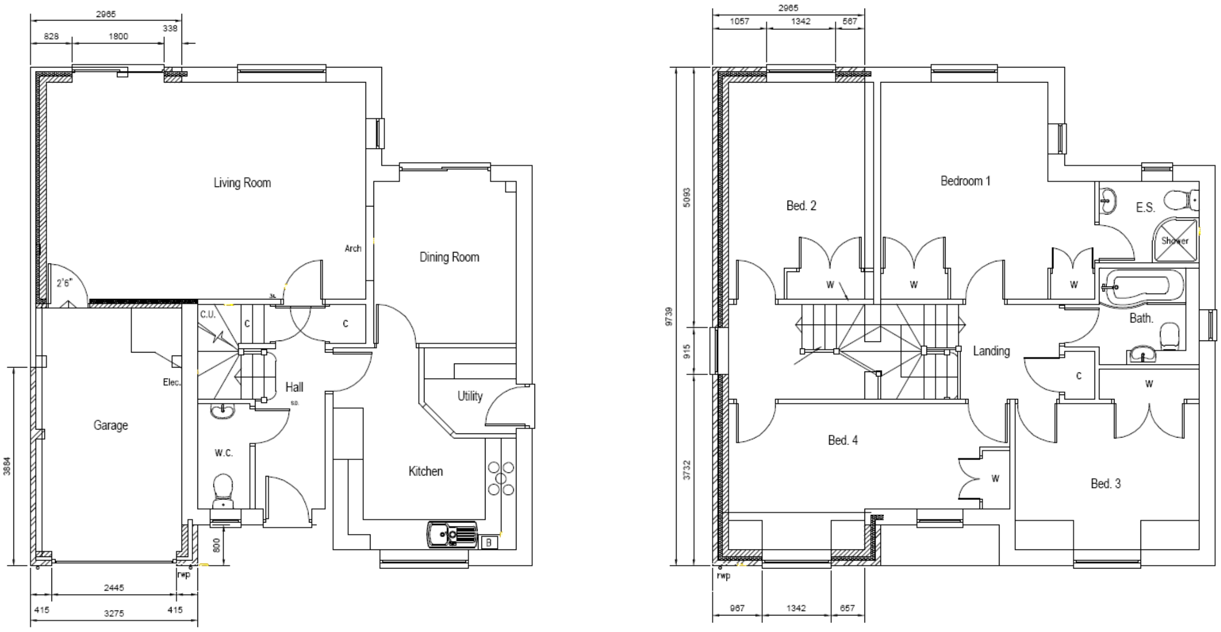
	Detached House ('Balanced' /nZEB)[1]	E0	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10
Air permeability rate ($m^3/h/m^2$ @50Pa)	1.0-5.0	6.0	3.5	5.0	2.5	2.2	1.5	2.5	2.5	2.0	1.0	1.0
Space heating/cooling demand ($kWh/m^2/yr$)	46	76	60	65	47	46	45	48	46	46	45	44
Annual Energy Consumption (kWh/m^2)[2]	10-19	135.91	86.15	88.96	17.64	19.12	17.34	19.60	18.79	17.69	17.03	16.32
Annual Carbon Emissions ($KgCO_2/m^2$)[2*]	10	51.73	26.38	27.81	10.56	9.94	7.73	10.75	10.12	9.59	9.20	8.16

[1] Values are obtained from Zero Carbon Hub [ZCH, 2009-216]

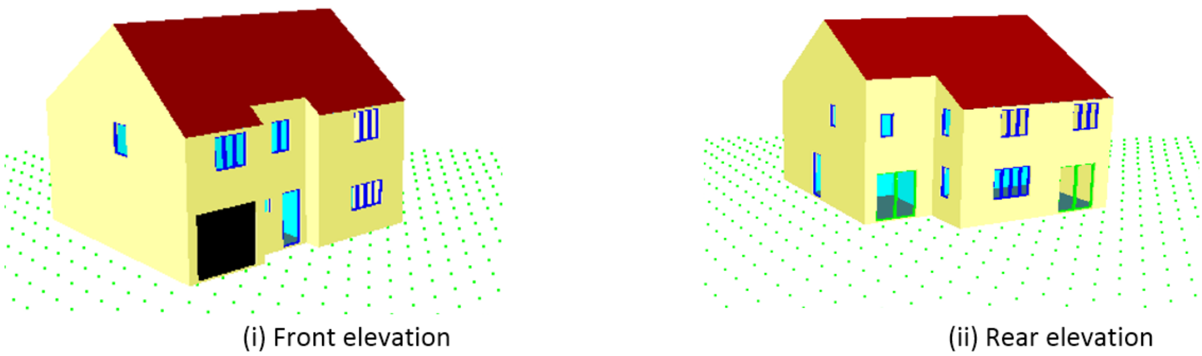
[2/2*] Final values are shown after displaced electricity (because of renewable/ trigeneration systems) has been considered where applicable

Accepted manuscript
doi: 10.1680/jensu.18.00055

Figure 1. Floor plans and 3d modelling outcome of the building case study [Salem et al., 2018]. (a) Floor plans of the case study building with a scale of 1:50. (b) Tas 3D Modelling results

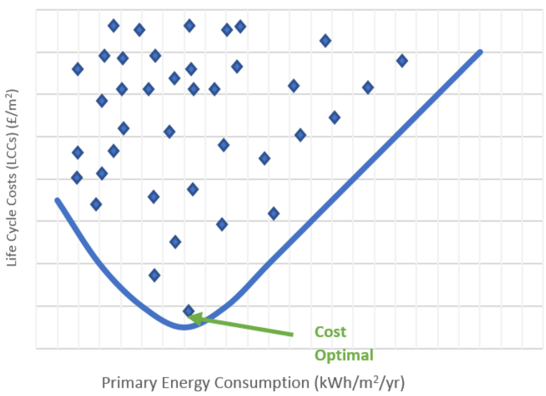


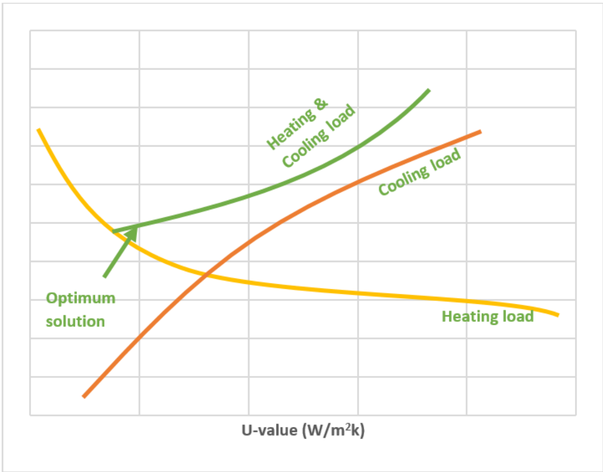
(a)



(b)

Figure 2. (a) Reproduced example of a cost-optimal curve. (b) Reproduced example of selection of the optimum u-value using TasGenOpt





Accepted manuscript
doi: 10.1680/jensu.18.00055

Figure 3. Breakdown of the various factors of the total LCCs

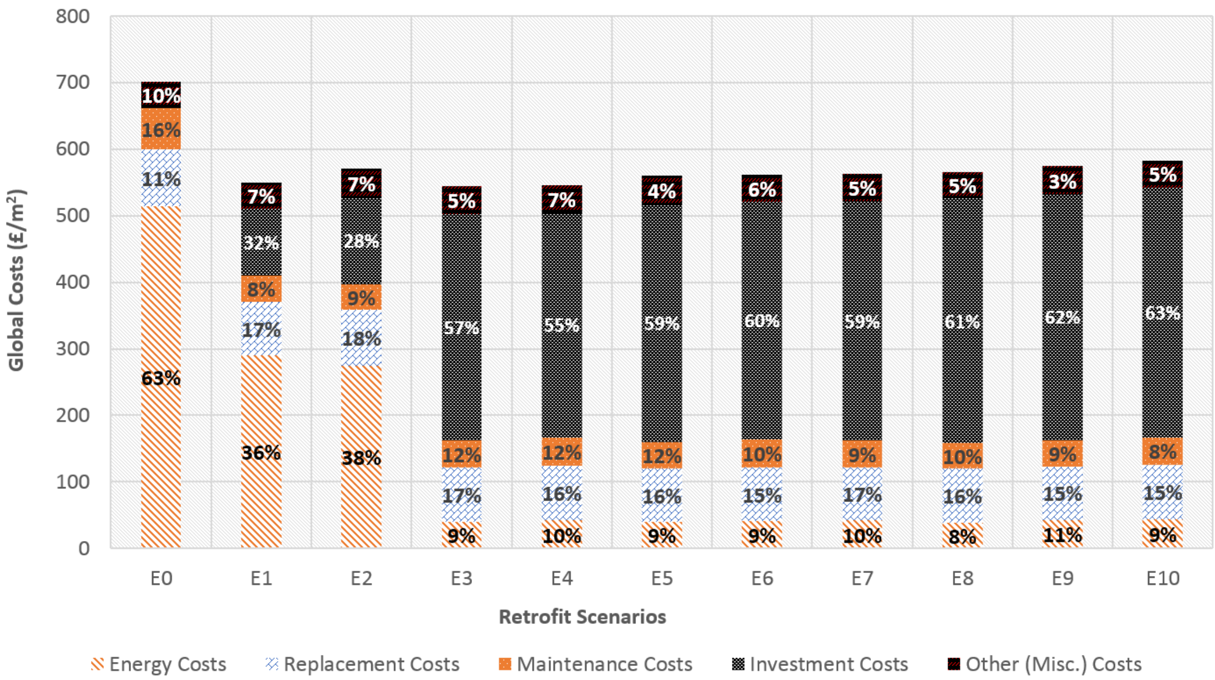
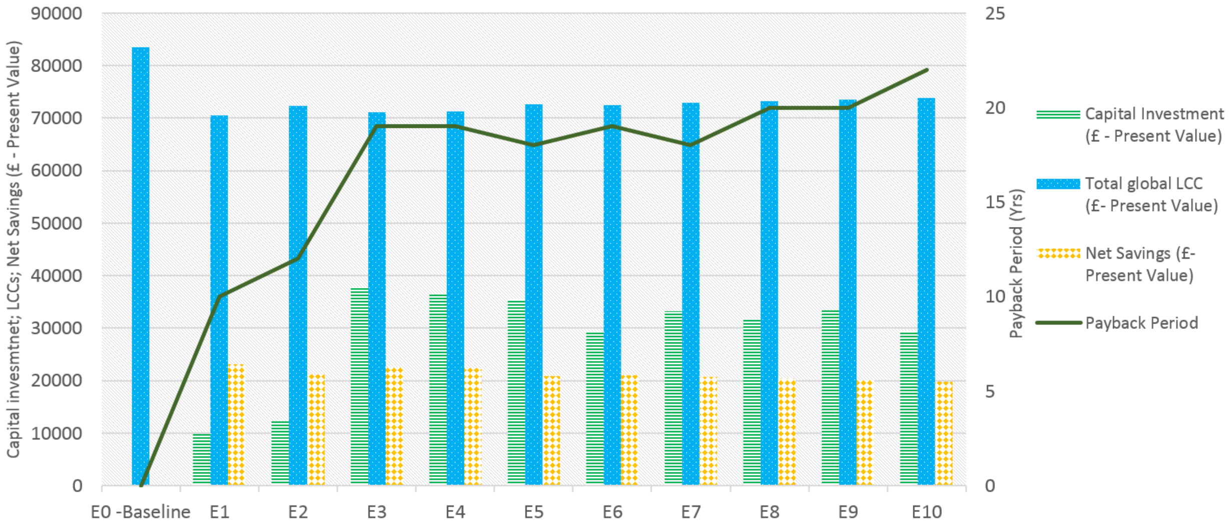
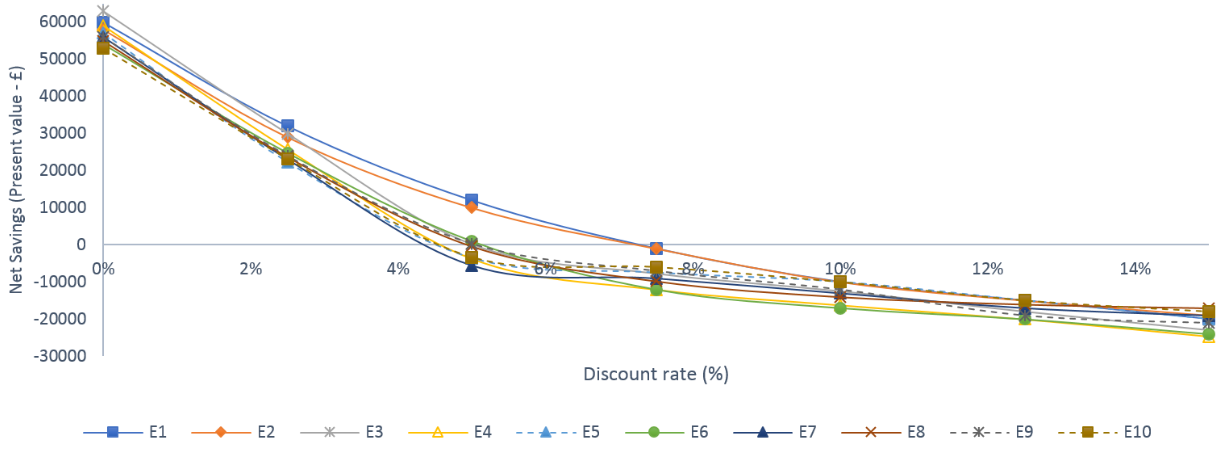


Figure 4. Results of the LCCs calculation for the various scenarios



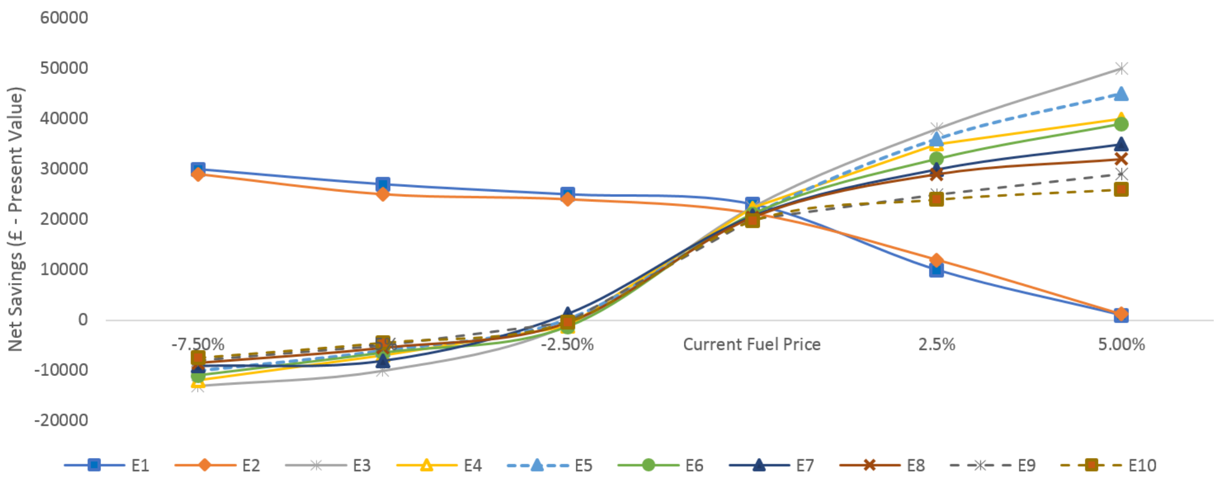
doi: 10.1680/jensu.18.00055

Figure 5. Effect of varying the discount rate on net savings (present value - £)



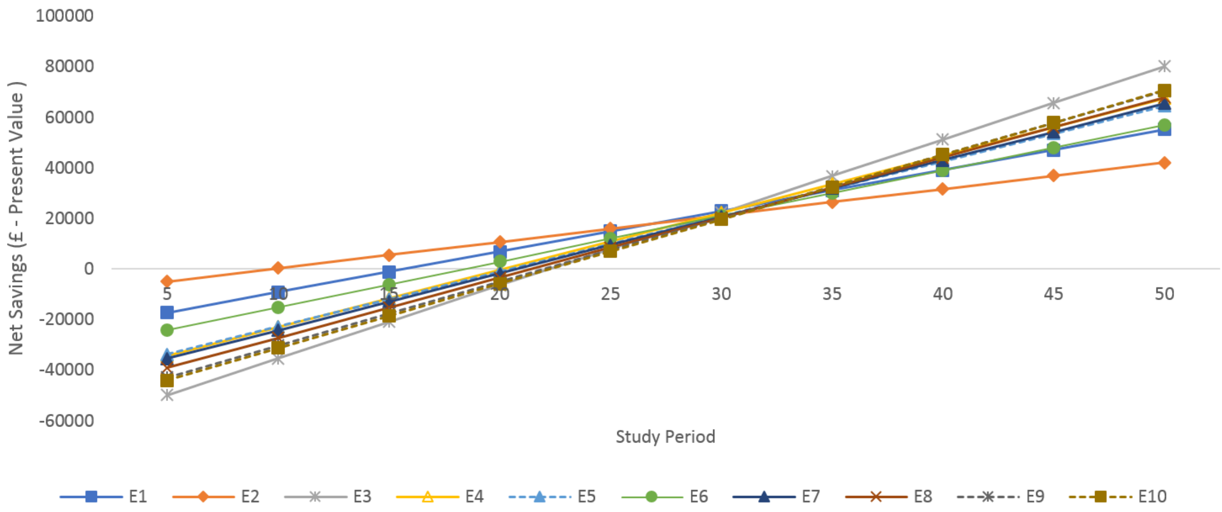
doi: 10.1680/jensu.18.00055

Figure 6. Effect of varying energy/fuel cost on net savings (present value - £)



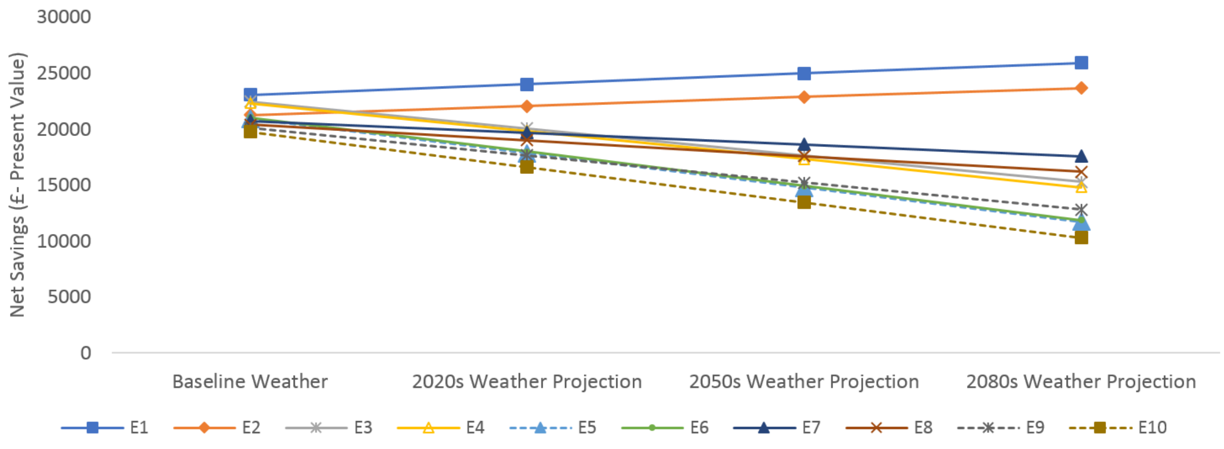
Accepted manuscript
doi: 10.1680/jensu.18.00055

Figure 7. Effect of varying the study period on net savings (present value - £)



doi: 10.1680/jensu.18.00055

Figure 8. Effect of varying the simulated weather data on net savings (present value - £)



doi: 10.1680/jensu.18.00055

Figure 9. Life cycle costs against primary energy consumption for all the retrofit scenarios