A Life Cycle Cost Analysis of an Irish Dwelling Retrofitted to Passive House Standard: Can Passive House Become a Cost-Optimal Low-Energy Retrofit Standard?

APPLIED RESEARCH INTO ENERGY RETROFIT TECHNOLOGY

A dissertation submitted to the Dublin Institute of Technology in part fulfilment of the requirements for award of Masters (MSc) in Energy Retrofit Technology.

By

Daniel Coyle BA(Hons) BArch MRIAI

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DUBLIN SCHOOL OF ARCHITECTURE,

DUBLIN INSTITUTE OF TECHNOLOGY

BOLTON STREET, DUBLIN 1

Head of School: Orna Hanly

Lead Supervisor: Dr Marek Rebow

Supervisor: Phil Cully

ABSTRACT

The existing Irish housing stock has been described as one of the worst performing in terms of energy efficiency in Europe, and will require a wide-spread and comprehensive programme of deep energy retrofitting if Ireland is to meet its commitments under the European Performance of Buildings Directive (EPBD recast), and achieve the required 80% reduction in CO_2 emission levels for the building sector by 2050, compared to 1990 levels.

The Passive House standard represents perhaps the current 'state-of-the-art' in low-energy building design, and is hailed by its advocates as a cost-optimal standard to be applied to both new and existing dwellings in order to achieve the necessary energy and CO_2 reductions. However, meeting the rigorous standards of Passive House in existing dwellings is demanding and generally requires significantly higher initial capital investments. This study aims to conduct an investment appraisal of the Passive House retrofit standard in order to determine if it could become a cost-optimal model for the deep-retrofit of Irish dwellings.

The problem is investigated using energy analysis (DEAP v3.2) and Life Cycle Cost Analysis tools (BLCC5), applied to a real-life case study Passive House retrofit - currently one of only three certified Passive House retrofit projects completed in Ireland to date. An individual approach is developed for assessing the project’s initial capital costs, as well as future operational costs. Total life cycle costs for the baseline (pre-retrofit) dwelling, the Passive House retrofitted dwelling, and a range of alternative retrofit scenarios are computed and Life Cycle Cost Analysis carried out for all alternatives.

Energy analysis of the case study building demonstrates that substantial reductions in estimated energy demand and CO_2 emissions (over 90%) can be achieved in a typical 'pre-regulations' Irish dwelling by deep retrofitting to the Passive House standard, which if applied on a wider scale could help meet Ireland’s energy reduction and carbon abatement targets.

An economic appraisal, using Life Cycle Cost Analysis together with sensitivity analysis, demonstrates that the deep retrofitting of an existing dwelling to the Passive House standard can also be cost effective, but only when longer investment periods (≥ 30 years), low discount rates (≤ 4%), positive fuel inflation (≥ 4%) and inclusion of residual values are considered. There is uncertainty and risk associated with the assumptions and boundary conditions of such an economic appraisal.

The study concludes that the higher investment capital costs associated with Passive House deep retrofit can give economic benefits in the long term, but from a purely private, micro-economic perspective, a less intensive 'Shallow Retrofit' is likely to be more profitable, generating greater net savings over the assumed investment term. However, with lower interest rates, longer investment timescales or higher fuel inflation, Passive House can become the cost-optimal standard.

ACKNOWLEDGMENTS

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I would also like to thank Simon McGuinness and Ciarán Ryan, for providing me with access to the case study dwelling construction drawings, specifications, building costs data, operational energy data and other information necessary for carrying out the Life Cycle Cost Analysis.

Lastly I would like to thank Áine Hayden and my family for their endless support, and for allowing me the time and space to complete this MSc research programme.

DECLARATION

I hereby certify that the material submitted in this dissertation toward the award of Masters in Energy Retrofit Technology is entirely my own work and has not been submitted for assessment other than part-fulfilment of the award named above.

Signature of candidate: ____________________________

Date: 1st May 2015

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LIST OF ABBREVIATIONS

ach	Air changes per hour
AIRR	Adjusted Internal Rate of Return
BER	Building Energy Rating
BEH	Better Energy Homes Scheme
BLCC5	Building Life Cycle Cost Program (version 5)
CEN	European Committee for Standardisation
CHP	Combined heat and power
CO_2	Carbon dioxide chemical formula
CSO	Central Statistics Office
DEAP	Dwelling Energy Assessment Procedure
DECLG	Department of the Environment, Community and Local Government (Ireland)
DHW	Domestic hot water
DPB	Discounted payback
ECEEE	European Council for an Energy Efficient Economy
EN	European Standard
EPBD	Energy Performance of Buildings Directive
EU	European Union
EU-27	Total EU member countries (as of time of writing)
EWI	External wall insulation
HARP	Home-heating Appliance Register of Performance (database)
HRI	Home Renovation Incentive Scheme
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
LCA	Life Cycle Analysis
LCC	Life Cycle Costs
LCCA	Life Cycle Cost Analysis
MVHR	Mechanical ventilation with heat recovery
NEEAP	National Energy Efficiency Action Plan

NIST	National Institute of Standards and Technology (US)
NPV	Net Present Value
NS	Net Savings
NSAI	National Standards Association of Ireland
nZEB	Nearly Zero Energy Building
OM&R	Operation, Maintenance and Repair
Pa	Pascals (pressurisation units)
PHI	Passive House Institute
PHPP	Passive House Planning Package
PIR	Polyisocyanurate (insulation)
PV	Present Value
SEAI	Sustainable Energy Authority of Ireland
SCSI	Society of Chartered Surveyors Ireland
SHW	Solar hot water
SPB	Simple payback
SWH	Solar water heating
TAS	Thermal Analysis Simulation (software)
WLC	Whole Life Costs

CHAPTER 1: Introduction

1.1 Climate change and the challenge of deep retrofit

It is clear that meeting Ireland's commitments to reducing emissions under current international climate change agreements (IPCC, 2014) and EU directives (EPBD, 2010) will require a sea change in our approach to energy use and energy conservation in buildings. With greenhouse gas emissions associated with the construction and operation of buildings accounting for an estimated 40% or more of Ireland's total emissions (SEAI, 2014), it is inevitable that the construction sector has become one of the key areas for emission reductions. On top of this, objectives to reduce energy use and promote fuel security, as well as addressing fuel poverty and the rising energy costs for users of buildings, will require a significant shift in our approach to the design and construction of buildings.

The European Performance of Buildings Directive (recast), has mandated a target of achieving an 80% reduction in CO_2 emission levels for the building sector by 2050, compared to 1990 levels (EPBD, 2010; COM, 2011). Whilst improving the energy performance standards of new buildings is an important part of this challenge, the current very low replacement rate of existing buildings, combined with their generally long life-span (100+ years), focuses on the importance of upgrading the current existing building stock through a major energy retrofit and refurbishment programme. With average replacement rates for existing housing stocks in the EU cited as less than 0.1% (Bell, 2004), the majority of Ireland's current dwellings will still be in place in 2050, and moreover the majority of these existing buildings will in general still have poor energy performance standards. It is apparent that it will be an enormous challenge to bring all of the existing stock up to a level of energy efficiency to meet our carbon emissions reduction targets.

1.2 Ireland's existing housing stock

The existing Irish housing stock has been described as one of the worst performing in terms of energy efficiency in Europe, with the average Irish dwelling consuming over 25,000 kWh of primary energy - Figure 1.1 (Brophy, Clinch, Convery, Healy, King, & Lewis,1999; BPIE, 2011). Moreover CO_2 emissions for the average Irish dwelling have been stated as being 47% higher than the average dwelling in the UK and 104% higher than the EU-27 average (Ahern, O'Flaherty & Griffiths, 2013).

By the end of 2010, there was just over 2 million dwellings in Ireland, of which around 52% were built before the Building Regulations (and hence any minimum energy performance standards) first came into operation on the 1st June 1992. The residential sector in 2011 accounted for over a quarter of all primary energy used in Ireland and was responsible for 10.5 million tonnes, or 27% of energy related CO_2 emissions (CSO, 2012; SEAI, 2013).

Despite various energy upgrading and improvement measures carried out to the existing stock, much of it supported by grant aids and incentives under the Better Energy Home and Warmer Homes Scheme (12% of stock since 2006), the Building Energy Rating (BER) of the average existing dwelling in Ireland still remains a D1 (Figure 1.2), with an average primary energy consumption of 242 kWh/m2/yr (SEAI, 2013).

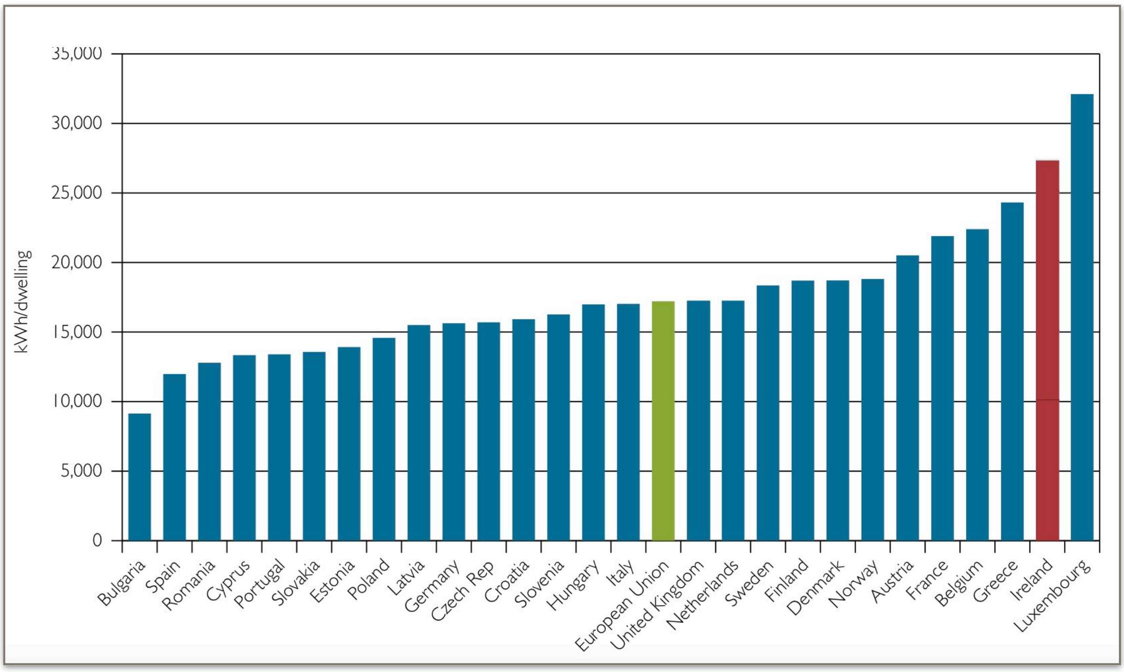


Fig. 1.1 Graph of EU-27 housing stock - average energy use per dwelling, with Ireland highlighted in red. (Source: Baeli, 2013).

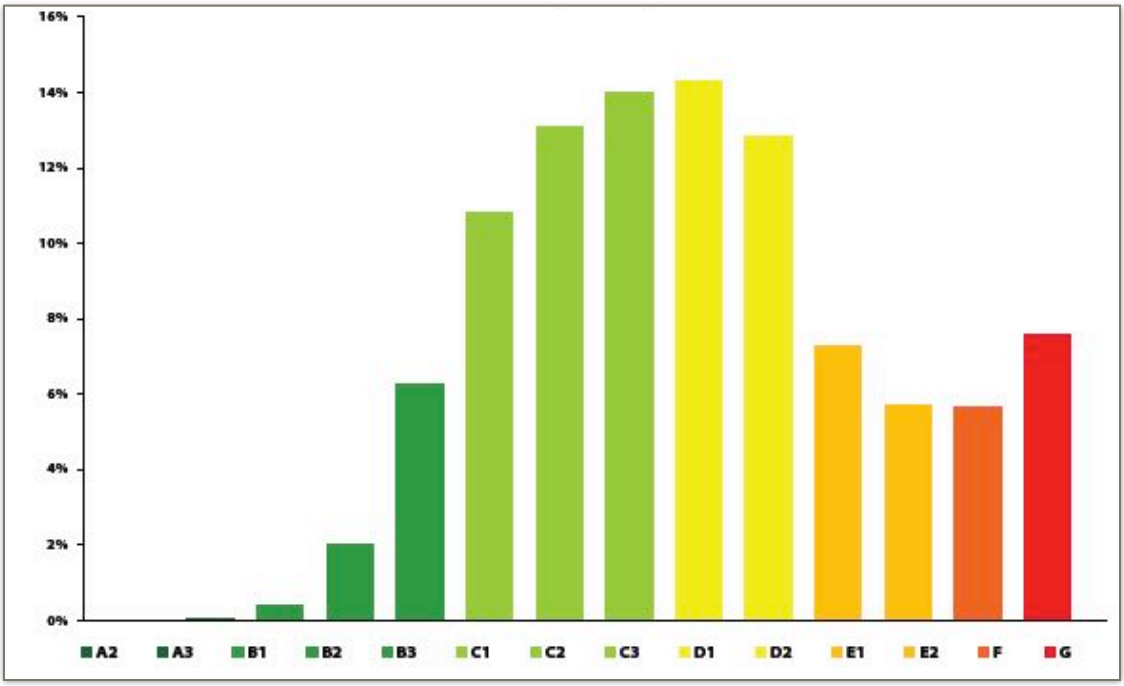


Fig. 1.2 Distribution of Building Energy Rating (BER) certificates for existing dwellings in the SEAI BER database. (Source: SEAI, 2013)

1.3 Deep fabric retrofit - application of the Passive House standard

Energy demand used for space heating in existing Irish dwellings on average accounts for over 67% of household delivered energy (SEAI, 2013). Given this fact, significant reductions in overall energy use and carbon emissions could be achieved with an intensive deep-retrofit of the thermal fabric of existing dwellings. This involves various measures to minimise heat losses; thermal fabric upgrades (insulation and high performance windows), reducing air-infiltration (air-tightness and draught sealing), recovery of ventilation heat losses (ventilation heat recovery), whilst maximising solar and other 'passive' internal heat gains, and combined with upgrades to energy-efficient space heating systems.

The Passive House standard represents perhaps the current ultimate in such 'fabric-first' low-energy building design, and is hailed by its advocates as a cost-optimal standard to be applied to both new and existing dwellings, in order to achieve the necessary energy and CO_2 reductions. Proponents of the Passive House standard, (and the marginally relaxed version for retrofitting existing buildings - EnerPHit), claim reductions of up to 90% in heating demand, energy demand and CO_2 emissions can be achieved (Figure 1.3). However, achieving the rigorous and comprehensive standards of Passive House in existing dwellings generally requires an increased degree of intervention and improved component standards, and hence significantly higher capital investments.

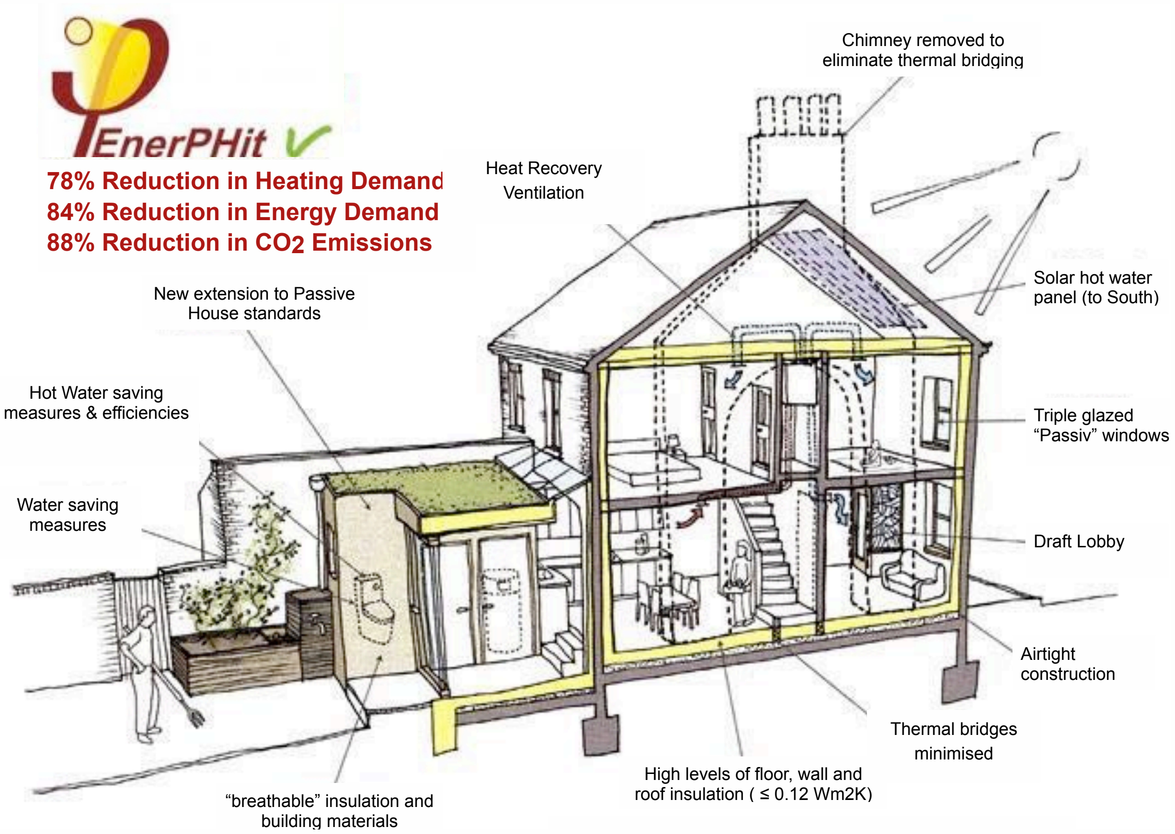


Fig. 1.3 Passive House retrofitting - main principles (Source: Anne Thorne Architects, 2015)

1.4 Financing deep retrofit - spending more to save more

The economics of energy retrofitting is based on the premise of 'spending to save' - meaning additional initial capital invested today in energy-efficient refurbishment measures should be balanced by energy cost savings in the future. Although there may well be co-benefits of implementing the Passive House deep-retrofit standard (improved comfort, indoor air quality, occupant health and wellbeing, reduced CO_2 emissions and environmental benefits), fundamentally it poses the question of whether the extra investment needed for such a high level of energy efficiency is economically feasible. Should we be spending more to save more? Do the financial savings accrued from ongoing reduced operational energy use over the whole life-span of the building justify the higher initial capital investment costs involved in retrofitting the dwelling?

Any attempt to answer this question requires in-depth economic analysis, using appropriate investment appraisal techniques. This means examining and properly quantifying all relevant capital and operational costs, occurring at different points in time, and over the whole life-cycle of an investment. Simple payback calculations (the amount of time it will take to recover the initial investment in energy savings) are not sufficient. Simple playback ignores the future costs and benefits occurring over the complete lifetime of a building, as well as the time value of money (inflation and interest rate).

The appropriate technique to conduct such an appraisal is Life Cycle Cost Analysis (LCCA). Such an investment appraisal needs to be an integral part of any capital budgeting or financial decision making, but in the writer’s view is currently very rarely carried out by construction professionals charged with designing and implementing dwelling retrofit and refurbishment projects.

Perhaps Passive House offers the potential to meet the required dwelling energy and emission reduction targets in Ireland, but can it also become a *cost-optimal* low-energy retrofit standard? This research question is investigated by carrying out an economic evaluation, using Life Cycle Cost Analysis, of a case study Irish dwelling retrofitted to the Passive House standard. The case study building, located in Galway City in the west of Ireland, is one of only three (at the time of writing) certified Passive House retrofits completed in Ireland to date.

1.5 Research aim and objectives

The primary aim of this research is to investigate whether it is more cost-effective for an individual private home-owner in Ireland to carry out energy efficient refurbishment measures to an existing dwelling in an intensive way (i.e. to the Passive House standard) in order to maximise operational energy use cost savings, or to adopt a less intensive retrofit strategy, requiring lower initial capital costs.

To meet the above-mentioned aim, the dissertation includes the following specific research objectives:

- Conduct a review of the literature relating to LCCA methods, tools and techniques, and 'cost-optimal' energy-retrofit standards emerging out of current EU & Irish energy policy and directives, and the international Passive House retrofit standard.
- Establish and review previous LCCA studies of low-energy building standards, in particular previous LCCA studies of Passive House.
- Arising out of the literature review, develop an appropriate LCCA methodology, to be adopted to allow an economic appraisal of the case study Passive House dwelling, including defining LCCA and energy-analysis calculation methods, software tools, data requirements, boundary conditions (economic assumptions), as well as the scope and limits of the analysis.
- Carry out a simple LCCA exercise (a sample problem) in order to test and validate the LCCA methodology, selected tools, and results of sensitivity analysis.
- Document and analyse the existing (pre-retrofit) and retrofitted construction standards, energy performance, initial capital construction costs and future operational costs of a 'real-world' case study Irish dwelling retrofitted to the Passive House standard.
- Carry out an economic evaluation (investment appraisal) using LCCA, of the case study dwelling. Compute the total net present value (NPV) and other key investment criteria for the Passive House retrofit, compared to a baseline, 'do-nothing' alternative. Conduct additional comparative LCCA calculations for the case-study dwelling using a range of alternative, intermediate retrofit scenarios.
- Determine whether it is more cost-effective to retrofit the existing dwelling to Passive House standard in order to minimise operational energy use, or to adopt a less intensive retrofit strategy, with lower capital costs.
- Carry out sensitivity analysis to assess the impact of changing economic variables (interest rate, fuel inflation rate, investment time-span) on life Cycle Costs. From the sensitivity analysis determine what are the economic conditions required to make the Passive House retrofit cost effective. Assess which of the economic variables is the most influential on the cost effectiveness of the Passive House measures.
- Recommend further work and research that could be carried out and highlight areas which warrant further investigation.

1.5 Dissertation structure - chapter contents

A summary of the dissertation structure by chapter is as follows:

Chapter 1 of the dissertation introduces the research topic, motivation and background, and sets out the research aim and objectives.

Chapter 2 contains a review and appraisal of current literature relevant to the research aim and objectives. The main concepts of Life Cycle Cost Analysis and 'cost-optimal' retrofit standards are introduced, together with the advanced performance characteristics of the Passive House retrofit standard. Finally there is critical appraisal of some earlier studies concerned with an economic analysis of Passive Houses using LCCA.

Chapter 3 describes the research methodology: the research design, methods, techniques and tools adopted to address the research question. The primary cost data needed to carry out the economic analysis is set out, together with the calculation assumptions. This chapter also defines the scope and limitations of the study.

Chapter 4 then examines a methodology validation process - presenting the results and analysis of a simple LCCA study carried out in order to test and validate the adopted methodology, techniques and calculation tools.

The case study Passive House dwelling is documented and analysed in detail in Chapter 5. This section describes the construction and energy performance characteristics of the case study building, and summarises the calculated capital investment costs and operational energy costs, to be used in the LCCA calculations.

Chapter 6 presents and analyses the results of the study. The results include sensitivity analysis.

Chapter 7 looks at the main conclusions reached, together with recommendations for possible areas of future research.

CHAPTER 2: Literature Review

2.1 Life Cycle Cost Analysis - key concepts and standards

Life Cycle Cost Analysis (LCCA) is a technique for evaluating the total economic performance of a building asset or building element over its projected lifespan, or defined period of analysis. It can be described as the overall cost of constructing, operating, maintaining, repairing, renewal and disposing of an asset over its entire service life (ISO 2008a). LCCA is a procedure enabling comparative financial appraisals to be made, of two or more project alternatives, in order to select the one that has the lowest life cycle costs and hence is the most cost effective over the anticipated lifespan (WBDG, 2014; SCSI, 2012).

In the context of building design and low-energy retrofitting, LCCA is a powerful economic analysis tool that can be used by architects, engineers and other construction professionals to improve energy-related investment decisions. In terms of the implementation of an energy efficient retrofit standard, be it Passive House or some other alternative, LCCA allows the assessment of two key investment decisions: (1) Are the increased initial investment costs incurred today justified by lower operating costs in the future? and, (2) out of two or more potential investment alternatives, which is the most economical in the long run? The alternative with the lowest overall life cycle costs will be the most cost-effective choice, assuming that it satisfies all other performance requirements (Fuller & Petersen, 1995).

There are currently a number of methodologies and standards developed for the application of LCCA. In the US, where LCCA has been widely adopted for a number of years by federal and government agencies, the NIST (National Institute of Standards and Technology) has produced a LCCA software tool as well as a detailed guidance handbook: 'Life Cycle Costing Manual for the Federal Energy Management Program' (Fuller & Petersen, 1995). In Europe, a report published by Davis Langdon Management Consulting in 2007: 'Life Cycle Costing (LCC) as a Contribution to Sustainable Construction: a Common Methodology', details a research and development project to develop a common EU methodology for LCCA in construction (Davis Langdon, 2007a). More recently the International Standards Organisation (ISO) published ISO 15686:5 - 'Buildings and Constructed Assets - Service-life Planning - Part 5: Life Cycle Costing', which provides construction professionals with a standardised method of applying Life Cycle Costing. ISO 15686:5 sets out the principles of LCCA, definitions, methods of performing LCC calculations, defining the scope for LCC studies, approaches to dealing with risk and uncertainty, and also LCCA reporting and analysis techniques (ISO, 2008a).

This research adopts a similar Life Cycle Costs Analysis methodology in accordance with ISO 15686 to the evaluate the cost effectiveness of deep-retrofitting an existing Irish dwelling to the Passive House standard.

2.2 EU directives - the EPBD, energy efficiency and cost-optimality

The European Performance of Buildings Directive (recast), outlines long term objectives for all EU member states of decreasing the CO_2 emission levels for the building sector by 80% in 2050, compared to 1990 levels, and further the requirement for all new buildings constructed from 2020 onwards to be constructed as 'Nearly Zero-Energy Buildings' (nZEBs). Moreover, recognising that the largest energy and emissions saving potential is associated with the existing older building stock, the EPBD also places a requirement on all member states to develop strategies and incentives for the deep-retrofit of *existing* buildings to the nearly zero-energy standard (EPBD, 2010).

Retrofitting the existing building stock to these required levels will clearly require enormous financial investments by both governments and private individuals, and it is recognised within EU policy that to realise the full potential of these energy and emissions savings, the whole life-cycle costs of a building over its entire life-span must be taken into account, as opposed to just focussing on initial capital investment costs (BPIE, 2013). The use of LCCA and the concept of 'cost-optimal' building performance requirements has been introduced, defined as the ‘performance level which leads to the lowest cost during the estimated economic lifecycle’ (ECEEE, 2011, *p.4*)

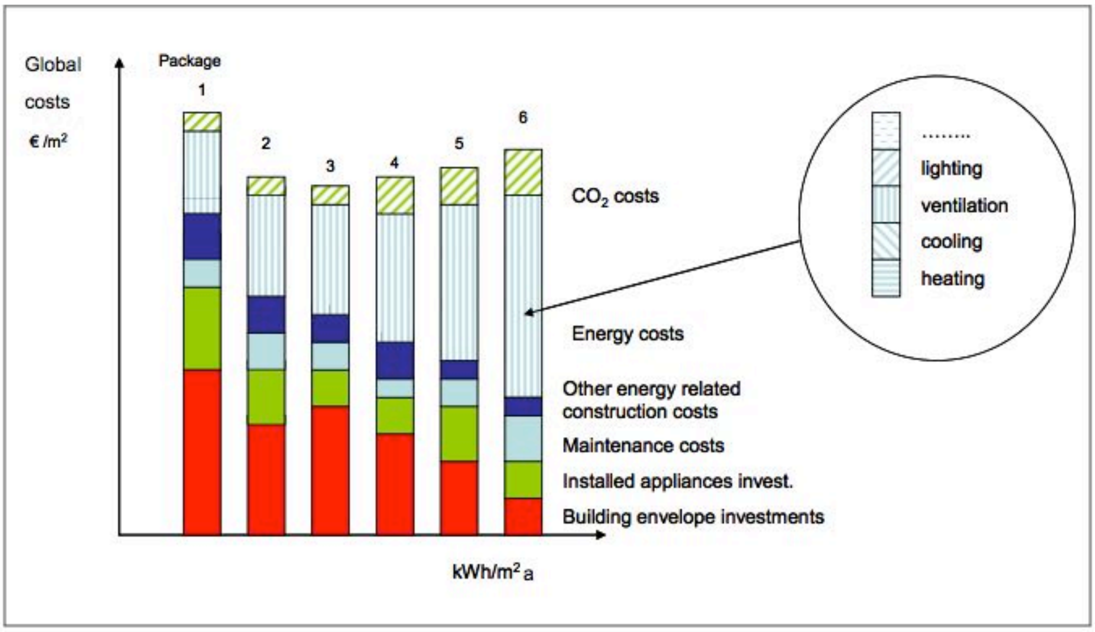


Fig. 2.1 Example of 'cost-optimal' calculations for 6 different packages - the package with the lowest Life-Cycle Costs *and* the lowest energy use should be the one selected (Source: ECEEE, 2011)

Article 5 of the EPBD requires all member states to determine cost-optimal standards for building energy performance and then to compare these with current adopted national standards (i.e. national building regulations). An EU comparative methodology is defined in the Regulations (EU Commission Regulation 244/2012), and expanded upon in the accompanying ‘Cost-optimal Guidelines’, which describe tools and standardised methods to calculate the global costs over the whole life cycle of a building, for a range of comparative retrofit 'packages' or energy efficiency measures, in order to determine which package is the most cost-optimal (Figure 2.1).

The objective of EU policy is for individual member states to develop cost-optimal models for energy efficiency solutions, based on a range of reference buildings and types. These cost calculations can be considered both at a private/end-users level (microeconomic perspective), as well as from a larger societal level (macroeconomic level), where the cost of CO_2 emissions, as well as social and environmental costs and benefits are also included. (ECEEE, 2011; BPIE, 2013)

2.3 Ireland's energy road-map: nZEB and cost-optimal retrofit standards

Ireland's current furthest vision for meeting its commitments under the EPBD in relation to energy reductions in the housing stock, is contained within a government policy document 'Towards Nearly Zero Energy Buildings in Ireland: Planning for 2020 and Beyond' (DECLG, 2012). This document commits Ireland to the implementation of increased minimum building standards to deliver near-zero energy dwellings by 2020. For a typical new dwelling this will mean a primary energy load for space heating, fixed lighting and ventilation of 45 kWh/m^2/yr (calculated using the Building Regulations' Dwelling Energy Assessment Procedure software, or 'DEAP'), equating to a Building Energy Rating (BER) target of A2 or higher.

In relation to existing dwellings, policies and measures are focused on 'market activation' of the Nearly Zero Energy standard in existing dwellings by 2020, with a target energy load for space heating, fixed lighting and ventilation of 125-150 kWh/m^2/yr, equating to a Building Energy Rating (BER) target of C1 or higher, with 'a reasonable proportion of the remaining energy use of the dwelling coming from renewable energy sources onsite or nearby'. (DECLG, 2012, *p.39*). However it is open to debate as to whether delivering the required energy and emissions reductions across the existing housing stock with such a relatively 'shallow' retrofitting of building fabric is cost-effective, or even achievable, given the sizeable input of on-site renewable technologies that would be required (i.e. large roof-mounted photovoltaic arrays) to offset the significant remaining energy demand and CO_2 emissions.

A study by Pountney, Ross, & Armstrong (2014) claims to be the first cost-optimal assessment of buildings in Ireland undertaken in accordance with the EU directive and methodology (Article 5 of the EPBD). This study defines an extensive set of notional reference buildings (dwelling typologies), examines the impact of a range of different packages of energy efficient measures (fabric, heating systems, and renewables technologies), and calculates their life-cycle costs.

The calculation then plots primary energy (kWh/m^2/yr) against global life-cycle costs for each alternative in order to build up a cost-optimal curve. The cost-optimal point is the package located along this curve with the lowest Life Cycle Costs *and* lowest primary energy (Figure

2.2). The EU directive mandates that the primary energy demand of national standards should be no greater than 15% of the cost optimal point (described as the 'cost-optimal range').

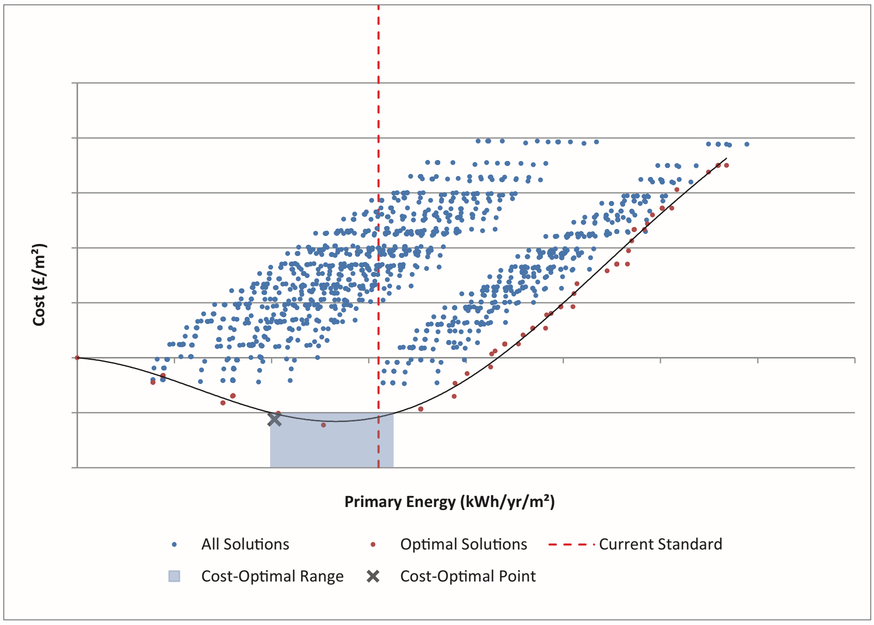


Fig. 2.2 Example of cost-optimal curve for sample reference building (Source: Pountney *et al*, 2014)

The assessment by Pountney *et al* concludes that for new-build dwellings the current Building Regulation dwelling energy performance standards (Part L 2011), are already within or in some cases exceed the cost optimal range. However, the assessment of the cost-optimal range for existing dwellings (retrofitting) is far less developed, and analysis is more at a building element level (e.g. cost-optimal levels of insulation thickness). The supporting cost-optimal calculations report (DECLG, 2013) gives some preliminary results of cost-optimal standards for individual building components (boiler replacement, replacement windows, wall, floor and roof insulation measures), but the study notably fails to give any kind of comprehensive 'whole-building' analysis, and its conclusions are somewhat unclear.

2.4 Passive House and EnerPHit retrofit standards

The Passive House (or Passivhaus) standard, an international construction standard developed by the Passivhaus Institute in Germany, represents perhaps the current ultimate in low energy building design and construction. It is a voluntary design standard that rigorously defines minimum fabric and systems performance criteria for achieving extremely low levels of space heating and total energy consumption within a dwelling, with the aim of producing buildings that can generally be heated mainly by passive means (solar and occupancy gains) and without the requirement for conventional space heating or cooling systems (Feist, Pfluger, Kaufmann, Schnieders, & Kah, 2007; SEAI, 2008).

The main principles for the construction of Passive House buildings are:

- optimised fabric insulation levels (very low U-values),
- elimination of thermal bridging (continuity of insulation layers),
- air tight construction (draught free and minimal air leakage),
- triple glazed windows with thermally-broken frames (Passive House certified windows),
- high level of indoor air quality maintained by an efficient mechanical ventilation system with heat recovery (MVHR).

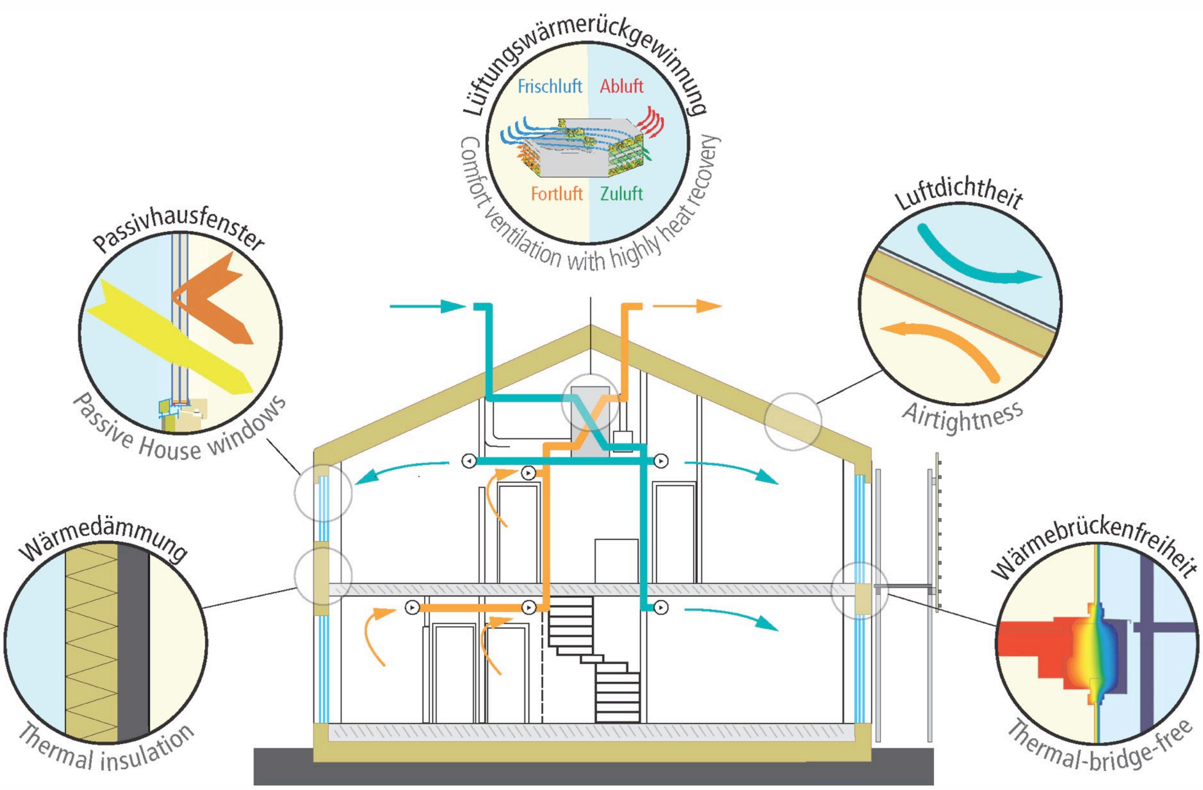


Fig. 2.3 Five basic principles of the Passive House standard (Source: Passivhaus Institute, 2015a)

A variety of construction (and retrofit) methods can be employed for Passive House design, although external insulation is widely employed in Passive Houses due to its ability to eliminate thermal bridging that may otherwise occur at the junction of structural members (i.e. between floors, walls, and roof).

More recently a version of Passive House has been released for refurbishment projects - EnerPHit. Recognising that achieving the full Passive House standards in the refurbishment of existing buildings may not always be achievable, the EnerPHit standard allows marginally relaxed requirements for space heating demand, airtightness, and thermal bridging. (Passivhaus Institute (PHI), 2015b) The relative performance criteria required to meet the full Passive House and EnerPHit standards are set out in Table 2.1 below.

Table 2.1 Passive House / EnerPHit standards - key performance criteria (PHI, 2015a & 2015b)

	Passive House	EnerPHit
Max. annual space heating demand	≤ 15 $kWh/m^2/yr$	≤ 25 $kWh/m^2/yr$
Max. space heating load	≤ 10 W/m^2	N/A
Frequency of overheating (> 25 ºC)	≤ 10 %	≤ 10 %
Max. annual primary energy	≤ 120 $kWh/m^2/yr$	≤ 132 $kWh/m^2/yr$
Airtightness (n50 pressurisation test)	≤ 0.6 ach @ 50 Pa	≤ 1.0 ach @ 50 Pa
Wall, floor & roof U-Values (recommended limit)	≤ 0.15 $W/m^2 K$ (1)	≤ 0.15 $W/m^2 K$
Window Installation (recommended limit)	≤ 0.85 $W/m^2 K$ (2)	≤ 0.85 $W/m^2 K$
Thermal bridging (max Ψ - psi values)	≤ 0.01 W/mK	minimised (3)
MVHR heat recovery efficiency	≥ 75%	≥ 75%
MVHR electrcity demand	max. 0.45 Wh/m^3	max. 0.45 Wh/m^3

NOTES:

(1) These are recommended but not mandatory maximum U-Values for fabric elements. Actual U-Values required depend on the building geometry, volume, glazing ratio and other compensating factors.

(2) This refers to the whole window installation U-Value, including glazing, frame and installation factors.

(3) Any significant liner thermal bridge with a psi value greater than 0.01 W/mK should be calculated and accounted for in PHPP.

2.5 Passive House cost optimal studies

A central claim of the Passive House movement is that it represents a cost-optimal standard for both new buildings and retrofit, as the extra investment in energy efficient measures can be balanced by energy cost savings over the building's lifetime (Feist, 1997). A Passive House Institute study (Research Group on Cost Efficient Passive Houses [AKKP42], 2011) examined the economic feasibility of Passive House retrofits using LCCA, as well as discussing the boundary conditions (economic variables) used for the financial calculations. Firstly this study highlighted that making proper retrofit investment decisions requires transparency regarding the assumptions - i.e. interest rates (which depend on an evaluation of risk), life-span of components, and the proper accounting of residual values at the end of the study period - factors all ignored by simple payback calculations (Passapedia, 2015a).

The other factor seen as vital in the financial appraisal of Passive House retrofit, is the proper separation of costs attributed to achieving energy savings from other incidental refurbishment costs. Buildings are not purely constructed for the purpose of saving energy. More often that not energy efficiency refurbishment will be combined with other non-energy related refurbishment and upgrade works. It follows from this that the condition or standard of the building prior to they retrofit strongly determines whether an energy saving measures can be considered economical or not. Existing buildings with very poor energy performance, and without any previous (sub-optimal) upgrade measures carried out will be more economical to upgrade to the Passive House standard (Passapedia, 2015a).

Moreover this study claimed that the higher levels of thermal insulation measures proposed by Passive House standards (e.g. up to 36cm of external wall insulation - figure 2.6) are also the cost-optimal, based on the principle of 'if it needs to be done, or if there is an opportunity to do it, do it as good as possible' (Passapedia, 2015b).

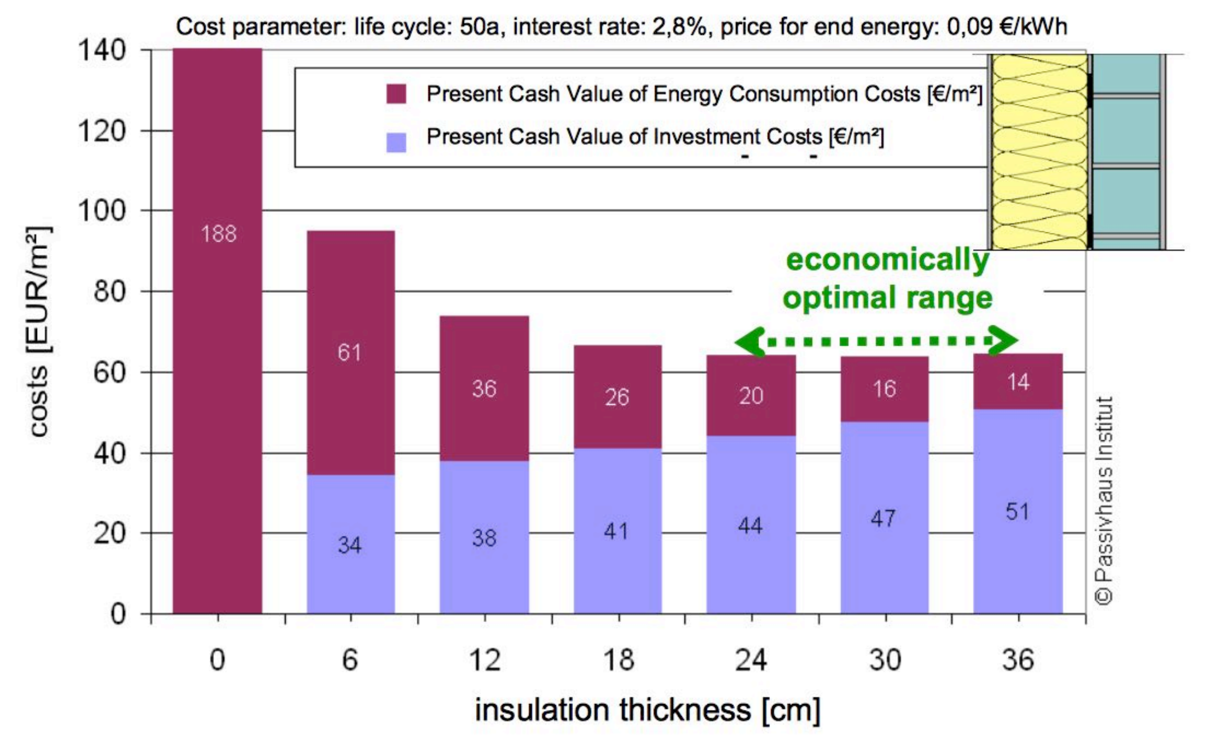


Fig. 2.4 Cost optimal external wall insulation thickness (Source: Passapedia, 2015b)

2.6 Other LCCA studies of Passive House

There are a number of independent studies that have examined the Life-Cycle Costs of different retrofit standards, including Passive House, in order to ask the question - does the retrofit standard with the lowest operational energy cost have the lowest total life cycle costs?

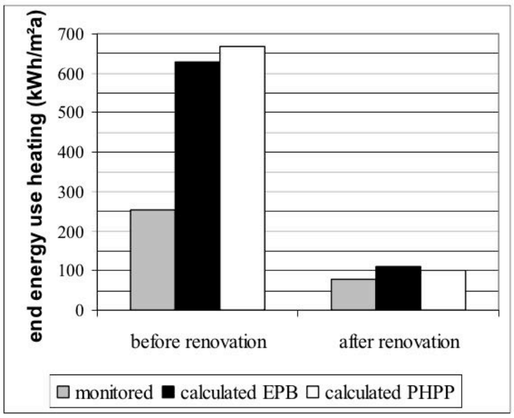
A study by Neroutsou (2014) used LCCA to determine the most cost effective way to refurbish the thermal envelope of a case study end of terrace Victorian house in London, by comparing the construction costs, energy savings, embodied energy, and embodied CO_2 of the original pre-refurbishment building, the actual as built 'regulations-compliant' retrofit standard, and a higher Passive House (EnerPHit) standard. For the three comparison cases, the author used TAS energy simulation software to calculate the predicted heating energy consumption, and LCCA to determine the Net Present Value of both initial capital costs, and all future operational costs and savings, calculated over an assumed 30 year investment period.

The results of this study suggested that the life cycle costs of the Passive House retrofit were 130% higher than the regulations compliant standard, and initially concluded that the additional initial capital costs of the Passive House standard would not be offset by the increased savings over the operational phases of the building.

Importantly though, Neroutsou recognised the many risks and uncertainties included in the economic analysis that can have a critical effect on the output results. Sensitivity analyses were carried out by individually changing a number of the key input variables - energy price inflation, discount rate, and extending the period of the study, giving different results and drawing an alternative conclusion that Passive House could be an economically optimal retrofit option, but only with rising energy prices, low discount rates (3.5%), and longer investment lifespans (more than 33 years).

An earlier Belgian study (Versele, Vanmaele, Breesch, Kein & Wauman, 2009) conducted a similar cost benefit analysis of energy retrofitting a 1950s singe family dwelling. Four different energy performance levels for retrofitting the dwelling were considered including Passive House. Energy costs were calculated using both PHPP and the Flemish national energy rating tool, EPB. The study found a 92% reduction in total end use energy could be achieved with the Passive House standard, compared with 81% from a less intensive 'low-energy' standard.

The cost optimal standard varied according to the predicted rate of fuel inflation, and the investment timescale - with a low fuel inflation forecast (2%), the Passive House retrofit failed to pay for itself, even after 40 years. Passive House was shown to be cost optimal only with a (perhaps improbable) 10% energy price increase every year, and over a 30 year investment horizon (This also correlates with the findings of Audenart, De Cleyn and Vankerckhove (2008)). As in Neroutsou (2014), the study highlighted the need for treating the conclusions of LCCA with care, with calculations based on multiple assumptions of retrofit construction costs, estimated energy savings (Fig. 2.5), interest rates, inflation and energy price escalation (Fig. 2.6) which are difficult to predict with certainty.



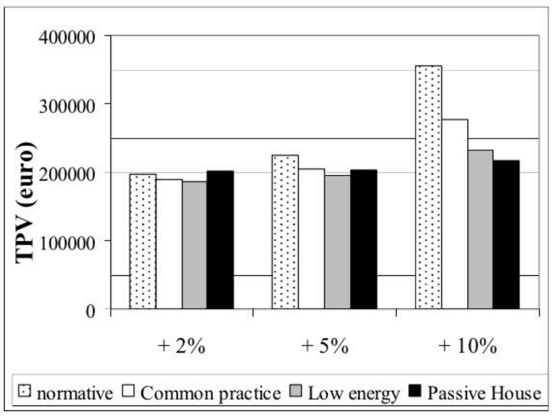


Fig. 2.5 (Left): comparison of calculated and monitored (actual) heating energy demand in the Flemish case study dwelling, **Fig. 2.6** (Right): Life Cycle Costs (Total Present Value) for retrofit alternatives with energy price inflation sensitivity analysis. (Source: Versele *et al*, 2009)

Famuyibo (2012) applied a similar LCCA methodology, but on a larger scale than just an individual case study building, in order to provide more generalised findings and policy guidance on the economic viability of applying the Passive House standard to retrofitting the entire Irish housing stock. As part of a much wider study on the Life Cycle Impacts and Carbon Emissions Abatement opportunities presented by low-energy retrofitting, Famuyibo first used statistical sampling, stock modelling methods, and the development of a range of representative dwelling 'archetypes'. This was then combined with LCA tools to try to determine the extent of National reductions in energy, life cycle costs and Carbon emissions that could be achieved in retrofitting the Irish housing stock to differing standards - meeting (current) Building Regulation standards, as well as to a more ambitious Passive House standard.

This study concluded that retrofitting the building stock to Passive House standard could reduce national life cycle primary energy-related emissions from dwellings by over 84%, but that both retrofitting to Current Regulations and to higher Passive House standard have significantly higher life cycle costs than the 'do nothing' BaseCase scenario (Figure 2.7). These findings would seem to be at variance with the results of Neroutsou (2014) and Versele *et al* (2009).

Scenario	Detached house archetypes	Semi-detached house/end-terraced house archetypes	Mid-terraced house/apartment archetypes	Stock total
BaseCase	21,350.0	6,304.3	4,930.7	32,585.0
Current Regulations	38,696.1	14,187.9	10,863.9	63,747.9
Passive House standard	52,662.1	21,670.7	16,208.4	90,541.2

Fig. 2.7 Total national discounted Life Cycle Costs (€ millions) by archetype for three different scenarios, calculated by Famuyibo for the Irish housing stock. (Source: Famuyibo, 2012)

2.7 Summary of Chapter 2

The main conclusions from this literature review chapter are the following:

- There is a huge energy and emissions saving potential associated with Ireland's existing housing stock, which is not being fully realised by current policy, standards, and financial incentives.
- Current and future EU energy performance policy and directives are placing a new impetus on member states to develop cost optimal, advanced energy-efficiency standards for *existing* buildings, in order to deliver on climate change and emission reduction commitments.

- Ireland’s current national policy and studies into cost-optimal retrofit standards for existing dwellings are somewhat vague and not yet clearly defined.
- There is debate as to whether it is more cost-effective to refurbish existing dwellings in an intensive way in order to minimise operational energy use, or whether it is better to adopt a less intensive retrofit strategy with lower capital costs and embodied energy.
- Retrofitting the existing housing stock to Passive House (or EnerPHit) standard could deliver major reductions (over 80%) in energy demand and CO_2 emissions. The Passive House movement contends that their retrofit standard is cost optimal, based on an proper economic assessment of long term life cycle costs, residual values, and accepting the principal of 'if it needs to be done….do it as good as possible'.
- Passive House deep-retrofit is expensive and the costs are unlikely to be justified on a simple payback basis. The true economic viability can only be properly assessed by Life Cycle Cost Analysis, to evaluate the total economic performance of the measures over their entire life-cycle.
- There are now clear established LCCA methodologies, tools and standards (ISO 15686:5) that can be adopted by construction professionals for the complete economic assessment of energy-retrofit projects.
- There is a degree of risk and uncertainty involved in LCCA, requiring sensitivity analysis. The results of life cycle cost calculations are highly dependant on the underlying economic assumptions and boundary conditions adopted.

CHAPTER 3: Research Design and Methodology

3.1 Life Cycle Cost Analysis - methodology overview

From an investigation of current Life Cycle Cost Analysis methods, standards, formulae and calculation tools, the research has adopted an appropriate LCCA methodology, for application to the economic assessment of the selected case study (a completed Passive House retrofit project). The methodology follows that of the international standard (ISO 15686:Part 5), and the draft EU CEN methodology: 'Cost optimal building performance requirements' (ISO, 2008a: ECEEE 2011).

Fundamental to LCCA is the consideration of all relevant costs occurring over the entire lifespan of an investment, and the use of discounted cash flows (all costs converted to their present value at the start of the project, taking into account the effects of interest rates and inflation). The research methodology first involves identifying and collating all the relevant cost data inputs and economic variables required to carry out a LCCA. A calculation of the Net Present Value (NPV) for project alternatives is then performed using the adopted LCCA tool and calculation formula, and the results presented and analysed. Sensitivity analysis is used to assess input data uncertainty and the effect of changing the key assumptions and economic parameters underpinning the calculations.

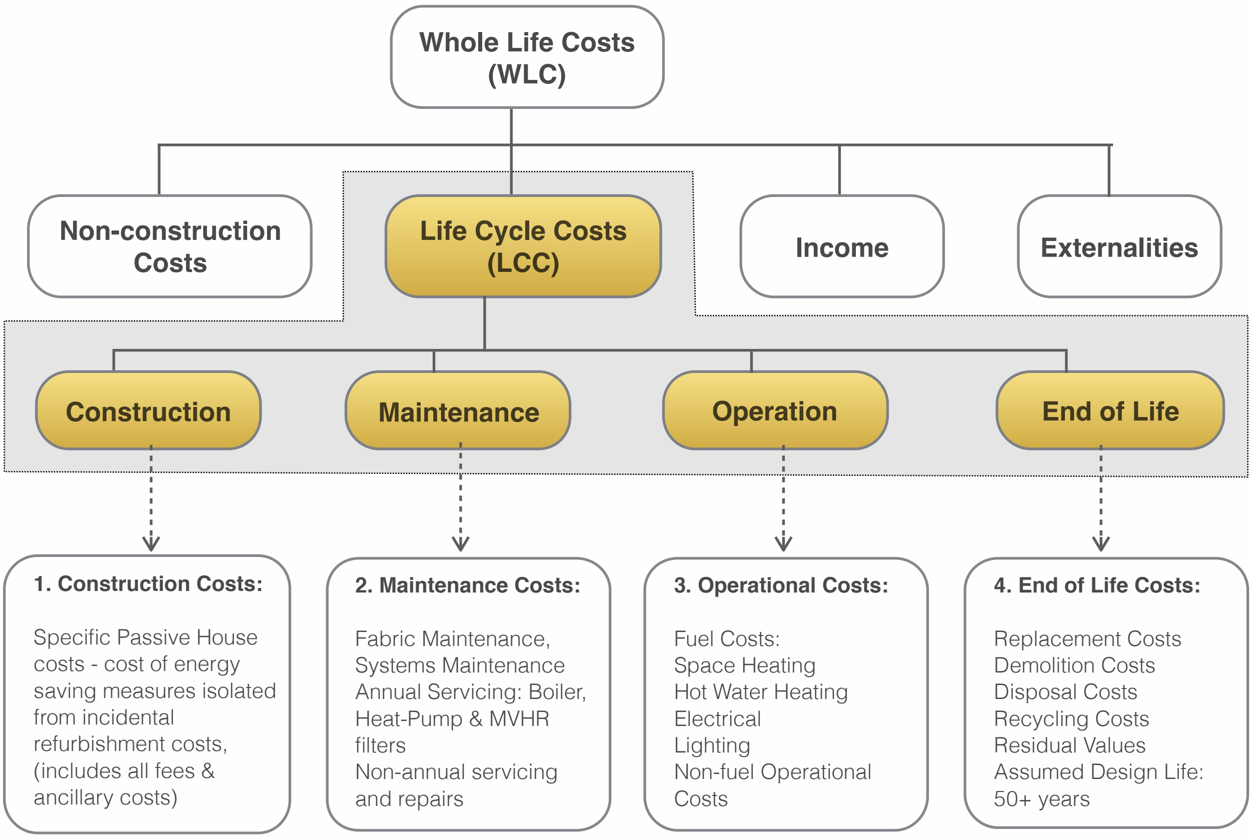


Fig. 3.1 Scope of Life Cycle Costs covered by the study, and cost data input requirements.

3.2 Scope and limitations of the LCCA study

The life-cycle costs associated with a particular building, component or project alternative should be seen within a larger realm of Whole Life Costs (Figure 3.1), that includes the following costs and benefits:

- non-construction investment costs (e.g. finance costs, land acquisition costs),
- project income (financial benefits generated by the project from sales or rent),
- externalities and non-monetarized costs and benefits (for example costs/benefits related to carbon emissions or general occupant health and wellbeing).

Furthermore it can be seen that different calculations of life cycle costs will be arrived at depending whether the analysis is considered from an individual perspective (private costs), or from a societal perspective (social costs). Depending on the perspective different assessments of interest rates, subsidies, taxes and environmental costs apply (Table 3.1).

Table 3.1 Private vs. societal analysis of life cycle costs. (Source: ECEEE 2011, p.25)

	Private Perspective	Societal Perspective
Interest rate	market interest rate (adjusted for inflation)	societal interest rate
Subsidies and incentives	included	excluded
Taxes (VAT and other taxes)	included	excluded
Cost of emissions	excluded	included

This research study is limited in scope to an analysis of the life cycle costs incurred by a private house owner. The societal perspective is not considered; monetarization of wider societal or environmental costs and benefits is therefore deliberately avoided. Co-benefits such as improved indoor air quality, improvements in user's comfort, health and amenity, and user satisfaction potentially brought about by a Passive House retrofit are excluded (even though it is recognised that there may be consequential economic benefits as a result of these improvements - i.e. increased work productivity, reduction in health-care expenditure etc.)

Similarly a reduction in carbon emissions and reduced dependency on fuel imports as a result of improved energy efficiency may have significant environmental and economic benefits on a national or state level, but such benefits are not currently transferred to the private investor by way of carbon taxes, tax rebates, subsidies or other financial incentives, and so are excluded from the cost analysis.

3.3 Life cycle cost formula

Life Cycle Costs (LCC) are the sum of all capital and operational costs occurring at different times over the life of a building or asset. A basic formula for the summation of all costs inputs is as follows:

$$LCC = I + OM\&R + Repl - Res + E$$

where,

LCC	-	Total Life Cycle Costs
I	-	Initial capital investment (construction) costs;
OM&R	-	Present-value operating (non-fuel), maintenance and repair costs.
Repl	-	Present-value capital replacement costs (components, or building);
Res	-	Present-value residual (resale, scrap or salvage value) less disposal costs;
E	-	Present-value energy costs;

For this research study, the LCC calculation requires the input of a range of key cost data related to the case study dwelling: (1) The initial capital investment costs (the specific energy efficiency retrofit costs), (2) (non-fuel) operating, maintenance and repair costs (e.g. annual boiler servicing, replacing of MVHR filters), (3) capital replacement costs (cost of replacement of the building, components or systems at end of life), (4) residual values (net of any disposal or re-sale costs), and (5) operational energy costs (in use energy costs).

It must be noted that LCCA involves a relative, or comparative analysis of differing economic investment options. Life cycle costs of one particular project alternative are only relevant when compared to another alternative with the same general project outcome. Consequently, it is not necessary to include each and every cost in the LCC calculation - 'Only those costs within each category that are relevant to the decision and significant in amount are needed to make a valid investment decision. Costs are relevant when they are different for one alternative compared with another; costs are significant when they are large enough to make a credible difference in the LCC of a project alternative'. (WBDG, 2014)

3.4 LCCA cost input data

3.4.1 Initial investment costs (energy retrofit construction costs)

The initial investment costs include all direct and indirect project and construction costs associated with achieving the energy retrofit performance standard. Direct costs are the construction costs paid to the main contractor and subcontractors to construct the retrofit works including the contractor's ancillary costs ('Preliminaries') and valued added taxes. Indirect project costs include professional fees, planning and statutory fees and charges, certification costs, as well as temporary accommodation or relocation costs during the retrofit works.

In other LCCA studies, estimates of capital construction costs are often taken from industry cost-benchmarks, or cost estimation guide-books (e.g. Famuyibo, 2012; Pountney *et al* 2014). The approach taken by this research however is to use cost data from a real-world completed Passive House retrofit project, based on the project architect's Final Account for the building works.

The methodology involves assessing all retrofit and refurbishment costs and separating costs into 'energy efficiency costs' (retrofit or renewal works attributable to improving energy performance), and 'incidental refurbishment costs' (general refurbishment, upgrade, or reconfiguration works required independent of any energy performance improvements).

Upgrading kitchen and bathroom fittings, altering internal room layouts, or proving new-build extension works are defined as incidental costs (works that do not have a substantial impact of the energy performance of the building). Installing insulation, replacing ground floor slabs (in order to install floor insulation), replacing windows and air-tightness measures are energy efficiency costs. Where costs are common across the two categories (e.g. professional fees, or rental costs) they must be spilt on a pro-rata basis using professional judgement.

3.4.2 Future maintenance, repair & replacement costs

Maintenance, repair and replacement cost are an integral part of overall life cycle costs (ISO, 2008a). Annually recurring maintenance and repair costs for the case study dwelling typically will include boiler or heating system servicing, changing of MVHR filters, cleaning of ductwork, and maintenance of air-tight seals to windows (Table 3.2).

Table 3.2 Estimated typical annual maintenance and repair costs for dwellings.

Building Element	Estimated Cost	Source
Oil boiler service	€100	Industry norm
Solid fire - chimney flue cleaning	€50	Industry norm
MVHR - change filters	€100	Installers advice
Cleaning window / door seals	€50	Installers advice

Depending on the chosen study period and expected total life-span of the dwelling, generally LCCA calculations are required to include any future replacement costs for building elements, equipment, and systems. This requires an estimation of the service life of such components in order to anticipate maintenance and replacement cycles. ISO 15686 gives guidance on service-life planning and estimation of life expectancy for building materials and components. Elsewhere there is a range of (somewhat differing) values in the literature regarding the expected useful service life of building elements or systems, annual maintenance costs, and renewal costs (ISO, 2008b; Famuyibo, 2012, Table 4.1, *p.*140).

The LCC calculations for this research include only capital replacement costs relevant to the energy retrofit measures. Replacement costs are assumed to be in line with current capital costs, (escalated to their future value). The service life and replacement of the relevant building components and equipment is assumed to be as per Table 3.3.

Table 3.3 Estimated service life and replacement costs for the dwelling.

Building Element	Service Life	Replacement Cost
Bathroom / kitchen extract fan	10 years	€100
Oil boiler	15 years	€2,500
MVHR - fan unit	20 years	€1,150
Heat pump	20 years	€9,000
Water pump (DHW)	20 years	€450
Window & door airtight seals	15 years	€100 / unit
Solar hot water panel	20 years	€4,000

3.4.3 Residual values

Retrofit and energy upgrade measures are constructed assets that will in general have a residual value at the end of the chosen study period. The residual value is the remaining economic value of the asset (building, systems or components), beyond the study period until the end of its useful lifespan. ISO 15686 suggests residual values be evaluated by ‘determining what similar, comparably-aged assets in similar locations are selling for in commercial markets', or where this is unavailable a 'straight-line depreciation based on the capital value and depreciation over the service life or design life of the asset’ (ISO, 2008a)

Both the US NIST and current EU CEN methodology suggest that as a rule of thumb, residual values can be calculated by linearly prorating the initial capital costs - i.e. expressed as a percentage of the initial capital investment costs. For example for a retrofit measure with an expected useful life of 50 years, and a study period of 30 years, the residual value would be approximately 40% of its initial capital investment costs (WBDG, 2014: Davis Langdon, 2007b).

It can be seen that the longer the estimated service life of the building, component or retrofit measures, the greater its residual value. Buildings in general have long life-spans; a minimum design life of up to 150 years (10-25 years for building services) is suggested in ISO 16686: Part 1 (ISO, 2011). The LCCA methodology adopted by this study assumes a life span of the energy retrofit measures of 50 years (seen as a reasonable assessment of the minimum design life of the installed insulation and thermal fabric upgrades).

3.4.4 Operational energy costs - calculation using DEAP

Annual operational (fuel) energy costs for all project alternatives are calculated using the DEAP (Dwelling Energy Assessment Procedure) energy analysis software. Although the case study retrofit dwelling has been designed to meet the Passive House performance criteria using the Passive House Planning Package software (PHPP), DEAP is currently the only recognised energy performance calculation tool that can be used to provide an energy performance rating and demonstrate compliance with Part L (Conservation of Fuel & Energy) of the Irish Building Regulations, in accordance with the EU Performance of Building's Directive (EPBD Recast Directive 2010/31/EU Article 3).

The DEAP methodology involves the user input of a wide range of parameters - dwelling floor area, geometry, exposed external surface areas, thermal properties (U-Values) of all fabric elements, window characteristics, ventilation systems, efficiency and responsiveness of heating and domestic hot water system, and fuel types (Table 3.4). From these inputs the software calculates expected annual delivered and primary energy consumption and associated CO_2 emissions for the dwelling under standardised operating conditions.

Table 3.4 Summary of main DEAP software inputs.

Element	Parameters
Building geometry	Building floor areas, living room area, floor heights, volume, exposed wall areas, roof areas, floor areas, window areas.
Building fabric	U-Values of elements, thermal bridging factor (Y-factor).
Windows	Orientation, glazing areas, U-Values, solar gains (g-value), over-shading, frame-glass ratio, thermal bridging for frames, solar & light transmittance values.
Ventilation	Air-tightness (infiltration rate), number of vents, fans & flues, draught stripping, type of structure (masonry or timber), site exposure, ventilation method (natural or mechanical), heat recovery efficiency.
Space heating systems	System controls & responsiveness, boiler efficiency, fuel type, distribution medium, distribution Losses, secondary heating system
Water heating systems	System controls & responsiveness, boiler efficiency, fuel type, distribution losses, storage losses, solar hot water systems
Lighting	Proportion of low-energy light fittings.
Renewables	Photovoltaic, biomass, CHP etc.

The DEAP software uses a range of standard assumptions regarding occupancy behaviour and energy use (number of occupants, heating set-point temperatures, heating schedules, electrical and domestic hot water usage), allowing different dwellings, or iterations of the same dwelling to be compared on a like for like basis (SEAI, 2015a).

DEAP is therefore an asset rating tool rather than operational (measured consumption), meaning it is designed to estimate the dwelling's energy performance and energy usage, not the occupants behaviour within it. Where available, (predicted) energy analysis results from DEAP should be cross referenced with actual measured energy use (in-use monitoring and fuel bills provided by the dwelling occupants).

Operational fuel costs for the LCCA analysis are obtained by multiplying the calculated annual Delivered Energy (kWh by fuel type) given in DEAP results page, by the relevant fuel price kWh unit costs (including VAT). These unit costs can be obtained from actual utility bills or from the current SEAI average National fuel price database (SEAI, 2015b).

Table 3.5 Average current domestic fuel costs, inclusive of VAT - 1/1/2015 (Source: SEAI 2015b).

Natural gas unit price €/kWh	Oil (kerosene) unit price €/kWh	Electrcity unit price €/kWh	Electricity night rate €/kWh	Coal / peat (solid fuel) €/kWh
0.0681	0.0755	0.2107	0.0971	0.0687

3.5 Present value analysis - calculating NPV of retrofit alternatives

LCCA involves looking at cash flows and costs occurring at different time periods of the life-cycle of a building. In order to be able to add and compare these costs LCCA calculations must convert all amounts to present values (the value of anticipated future occurring costs in 'today's money'), by applying a discount rate that reflects the 'opportunity cost of money over time'. For all future occurring costs the LCCA methodology first escalates the base year costs to their anticipated future time of occurrence, based on an escalation or inflation rate, and then discounts all costs to give *Net Present Value* costs (SCSI, 2012).

The Net Present Value (NPV) of a particular investment scenario is thus calculated using a formula combining the escalation rate (inflation), discount rate (interest), and the study period (investment period):

$$X_{\text{NPV}} = \sum (Cn \times q) = \sum_{n=1}^{p} \frac{Cn}{(1+d)^n}$$

where

C is the cost in year n;

q is the discount factor;

d is the expected real discount rate per annum;

n is the number of years between the base date and the occurrence of the cost;

p is the period of analysis.

3.6 Software tools to calculate NPV

Using the above basic mathematical formula a simple LCCA calculation tool can be developed using an Excel spreadsheet. Alternatively there are a range of LCCA software programmes available. One such programme is the BLCC5 software (Building Life Cycle Cost Program, version 5), developed by the US National Institute of Standards & Technology (NIST), and provided freely by the US Department of Energy.

The BLCC5 software requires user input of all life cycle cost data (initial capital investment costs and operational costs) as well as defining the economic boundary conditions (discount rate, escalation rate, investment period, service life and residual value factor) (Figure 3.2). The software will then compute (in present-value currency) total life-cycle costs for each project alternative, based on the inputted cost data and economic assumptions.

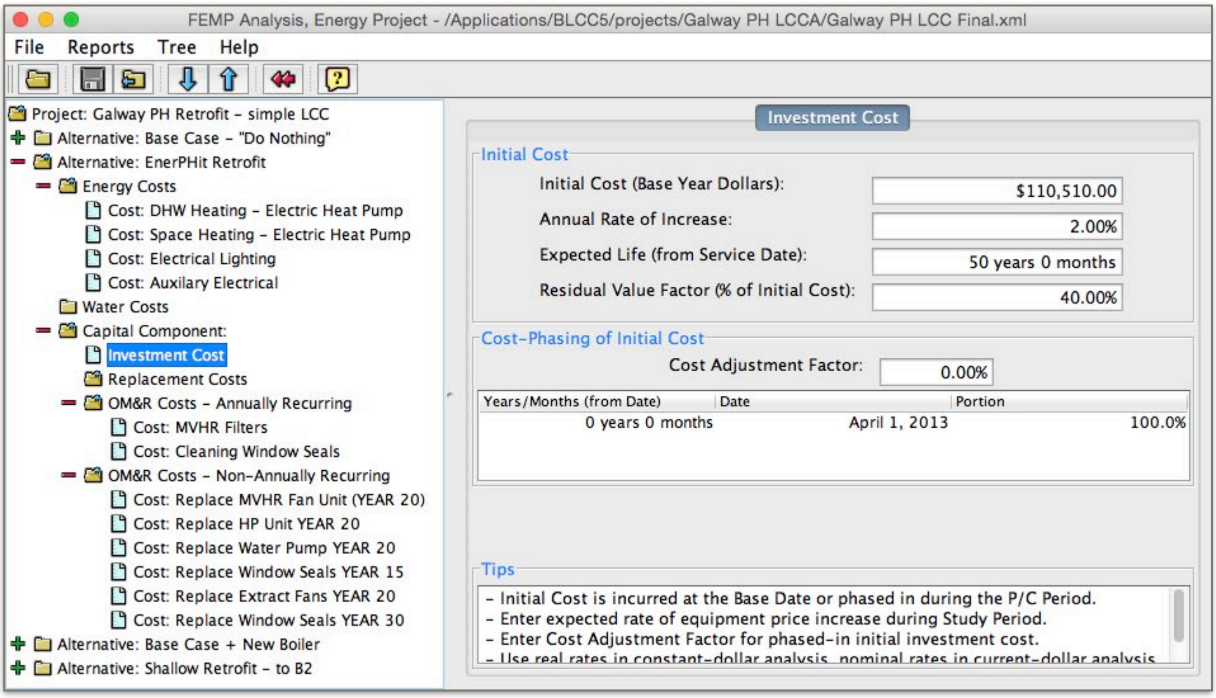


Fig. 3.2 Screen-shot of BLCC software program - user data-entry window (Investment Costs).

In addition to computing the total life-cycle costs for each project alternative (and highlighting the alternative with the lowest life-cycle costs) the BLCC software will also report supplementary economic criteria - including Net Savings (NS), Savings-to-Investment Ratio (SIR), Adjusted Internal Rate of Return (AIRR), Simple Payback (SPB) and Discounted Payback (DPB), which can all be used to guide investment decisions (Table 3.6).

Table 3.6 Supplementary economic criteria computed by BLCC5 software.

Criteria	Measurement
Net Savings (NS)	Operational savings less difference in capital investment costs.
Savings-to-Investment Ratio (SIR)	Ratio of operational savings to difference in capital investment costs.
Adjusted Internal Rate of Return (AIRR)	Annual yield from an alternative over the study period, taking into account reinvestment of interim returns at the discount rate
Simple Payback Period (SPB)	Initial investment divided by annual savings. Amount of time (years) required before the initial investment costs are recovered. Ignores 'time value of money', and also cash inflows and residual value of asset at end of payback period.
Discounted Payback Period (DPB)	Initial Investment divided by annual savings, but with all costs discounted to present values, to account for time value of money. Ignores cash inflows and residual value of asset at end of payback period.

3.7 Economic assumptions used in LCCA calculation

3.7.1 Discount rate

Perhaps the most critical assumption in LCCA calculations in the discount rate - representing the 'opportunity cost' of investing capital in the retrofit works, or 'a quantification of the uncertainty associated with benefits arising from investments' (Neroutsou, 2014). For private sector investments it should generally be taken from either the market interest rate of any mortgage or loan required for the investment, or alternatively the interest lost that could have been earned had the capital been left on deposit in a bank, or some other form of investment. For public sector investments it is normally determined by the central government rate, referred to as the 'social discount rate' (Davis Langdon, 2007b).

ISO 15686 refers to typical discount rates of between 0% and 4% (ISO, 2008a). Famiyubo (2012), used a Discount Rate of 4%, whilst Neroutsou (2014), used a rate of 3.5%. The cost-optimal assessment of buildings in Ireland by Pountney *et al* (2014) selected a rate of 7% for private sector investments, 'based on an assessment of the current financial landscape', and a 4% rate for public sector investments (the rate used by the Irish Government in policy-impact assessments). Irish Central Bank figures give an average annual interest rate (over the last 12 years) of 3.6% for variable interest house purchase mortgages, and average rate of 5.3% for general consumer loans (Central Bank of Ireland, 2015).

Higher discount rates will have the effect of discouraging long-term capital investments (the value of future costs or savings decreases), whilst low rates will encourage long term approaches and higher initial investments (future cost savings become more valuable). The research study will initially assume a discount rate of 4% (real rate - excluding inflation), based on an assumed average residential mortgage rate fixed over a 30 year term.

3.7.2 General inflation rate

Inflation is defined as a rise in general price levels reflecting a decline in the purchasing power of money over time. The historical annual inflation rate for Ireland averaged over the last 10 years was 1.2%, and over the last 20 years 2.23% (CSO, 2015). The LCCA methodology assumes an annual general inflation rate of 2% for all capital investment costs.

Net Present Value calculations can be carried out in either constant-Euro terms (excluding inflation) or current-Euro terms (including inflation), (Davis Langdon, 2007b). Where calculations exclude the effects of inflation, all costs (including future occurring costs) are expressed in terms of the base date currency, and use 'real' discount rates (i.e. a discount rate ignoring the effects of inflation or deflation).

3.7.3 Energy price escalation rate

Energy costs have historically been subject to price increases disproportionate to general inflation. Over the last 15 years, there has been a doubling of both domestic heating oil and electricity prices in Ireland, equating to an annual escalation rate of approximately 7% (SEAI 2013). Despite some recent drops in oil prices (20% reduction in heating oil price in Jan 2015; SEAI, 2015), fossil fuel prices are likely to continue a overall upward trend as global demand continues to grow and reserves diminish. The research will initially assume an annual fuel escalation rate of 4% (2% above general inflation rate).

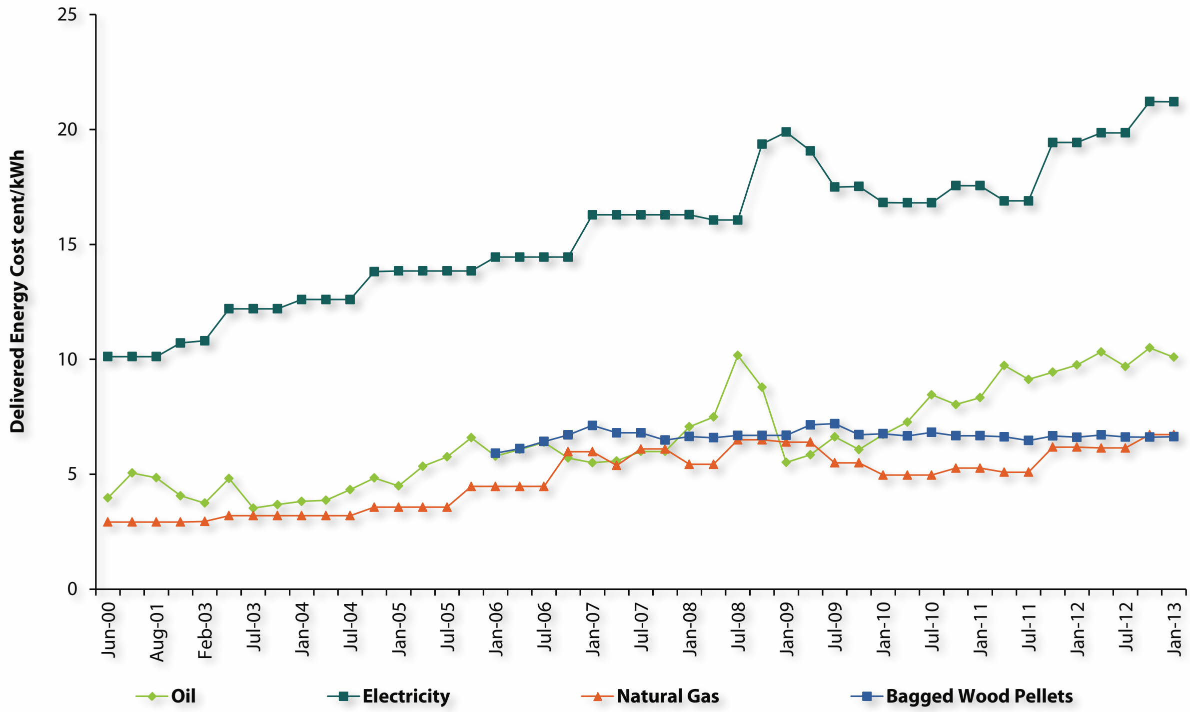


Fig. 3.3 Residential energy price trends (2000-2013) - fuel cost in Cent per kWh (SEAI, 2013).

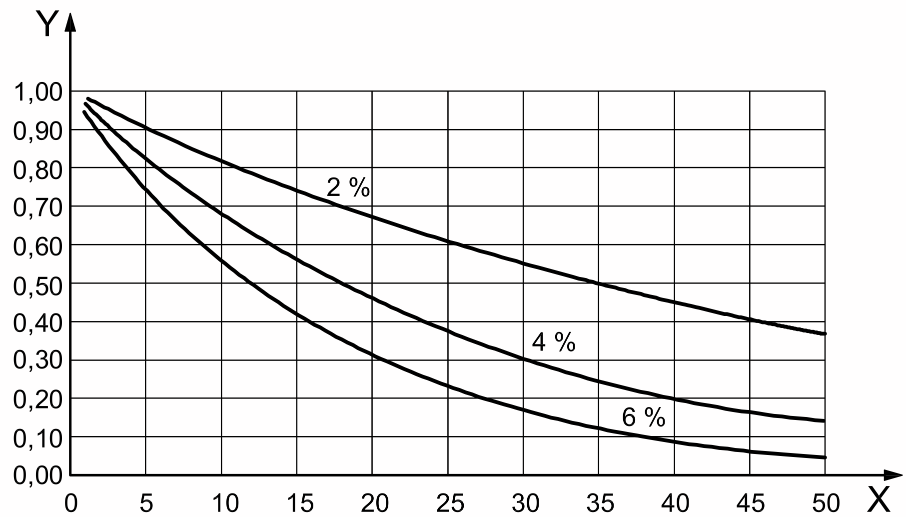
3.7.4 Study period

Another of the critical parameters in LCCA is the length of the study period - defined as either the service life or the period of time for which the investor has an interest in the building. The longer the investment time-span of the building or retrofit measures, the more the initial higher capital investment can be justified. Short study periods will encourage more minimal capital investments.

A 30 year study period is typically used in LCCA calculations for buildings (Neroutsou, 2014; ECEEE, 2011; Pountney *et al,* 2014) although other studies have suggested 40 years or more (Versele *et al*, 2009; WBDG, 2014). The research study will initially use a study period of 30 years; seen as the typical maximum term of any fixed interest loan offered by a bank, and a timespan beyond which any reasonable discount rate or energy price forecast becomes quite difficult.

3.8 Sensitivity analysis

It is apparent that LCCA is affected by a number of unpredictable economic variables fluctuating over time and hence contains an inherent degree of uncertainty. Changing any one of the key assumptions or parameters in a LCCA calculation can impact dramatically on the results of any investment appraisal (Figure 3.4). LCCA therefore must also involve a series of 'sensitivity analyses' in order to check the reliability and stability of the input data and assess the impact of changing individually, and in combinations, all of the key variables such as the discount rate, or predicted fuel inflation. (ECEEE, 2011, BPIE, 2013).



Key

X years in the future

Y present value

Fig. 3.4 Sensitivity analysis: effect of differing discount rates (2%, 4% and 6%) on present value of 1 unit of currency over a 50 year study period. (Source: ISO, 2008a)

3.9 Comparative life cycle cost analysis - retrofit alternatives

As well as comparing the life cycle costs of the as-built Passive House retrofit with those of the original pre-retrofit (baseline) dwelling, the study will also conduct additional comparative life-cycle cost calculations with some alternative notional retrofit scenarios. In this way, the retrofit alternative with the lowest Life Cycle Cost can be established. The study will identify in total 4 differing retrofit alternatives or scenarios, for which the complete Life Cycle Costs will be calculated and compared:

1. Original dwelling (base-case) - the 'do-nothing' scenario (DEAP calculated total primary energy of 386 kWh/m^2/yr - BER F rating).
2. Heating systems upgrades - i.e. a new 92% efficient condensing oil boiler and heating controls, new radiator system, heating and hot water installations (DEAP calculated total primary energy of 310 kWh/m^2/yr - BER E1 rating).
3. B3 'Shallow Retrofit' - basic fabric improvements (external insulation, double-glazed windows) system improvements (efficient boiler and controls), and renewables (solar hot water panel) - upgrade to B3 BER rating (DEAP calculated total primary energy of 136 kWh/m^2/yr).
4. Passive House retrofit (as-built) - (DEAP calculated total primary energy of 43 kWh/m^2/yr - BER A2 rating).

3.11 Summary of Chapter 3

The main conclusions from this methodology chapter are,

- The scope and limitations of any LCCA study need to be well defined at the outset. This study is primarily concerned with an economic analysis from the private perspective of an individual home-owner. Taxes and incentives will be included, whereas CO_2 emissions and other societal costs and benefits will be excluded.
- LCCA requires assembling cost data for the case study project - initial capital investment costs, maintenance, repair and renewal costs, and annual operation energy costs.
- Only the specific costs of each project alternative that are relevant to the investment decision and significant in amount need to considered in the study.
- The study will use DEAP energy analysis software to calculate operation energy use, and the BLCC5 Program to calculate life-cycle costs (Net Present Values) for each of the project alternatives.
- For the initial analysis the study will adopt a 30 year investment term (study period), 50 year life-span, 4% discount rate, 2% general inflation rate, 4% fuel inflation rate, and 40% residual value.

- Sensitivity analysis is required to assess uncertainty and risk. The purpose of sensitivity analysis should be to assess not only the impact of fluctuating variables, but to see which of the variables has the most impact on the results, and moreover to determine *which set of economic variables is required to make the Passive House retrofit the cost-optimal alternative*.
- A summary of the proposed LCCA methodology is as follows:

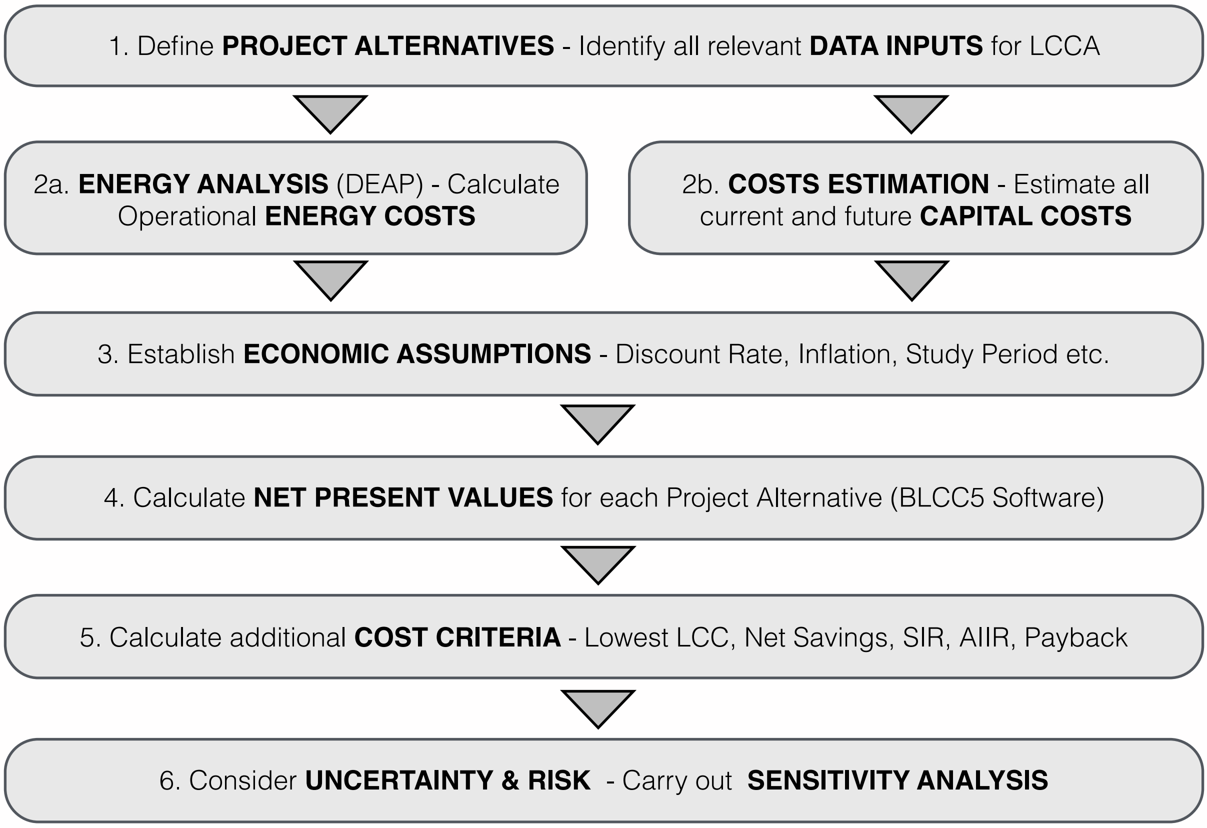


Fig. 3.5 LCCA process flow chart

CHAPTER 4:   Validation of Methodology - Simple LCCA Investment Scenario

In order to test and validate the LCCA concepts, methodology and software tools described in the previous chapter, a simple example LCCA investment appraisal was carried out. This involved taking a notional investment scenario with minimal variables and inputs. LCCA calculations were carried out using both an Excel spreadsheet (Appendix B), and also the BLCC5 software. This allowed for testing and validation of the software tool - the two calculation methods were seen to closely correlate.

The scenario involved a typical common retrofit decision faced by many homeowners - whether to replace an existing domestic gas boiler, of average efficiency, with a new 'A-rated' condensing boiler. There are (predicted) energy and CO_2 emissions reductions from such a retrofit measure, but is it cost effective, or *profitable* to replace the boiler? Are the initial capital costs recouped over the investment time period?

4.1   Assumptions used for replacement boiler LCCA calculation

The existing boiler is fully operational and installed into an existing 2-bedroom terraced dwelling house of approximately 100 m^2 (not the case study dwelling). The heating system is a standard hot water radiator central heating system with thermostatic radiator valves, main programable time and temperature controls, and indirect hot water storage cylinder but without separate domestic hot water controls or boiler interlock. The existing boiler is assumed to be 75% efficient (from the HARP boiler database).

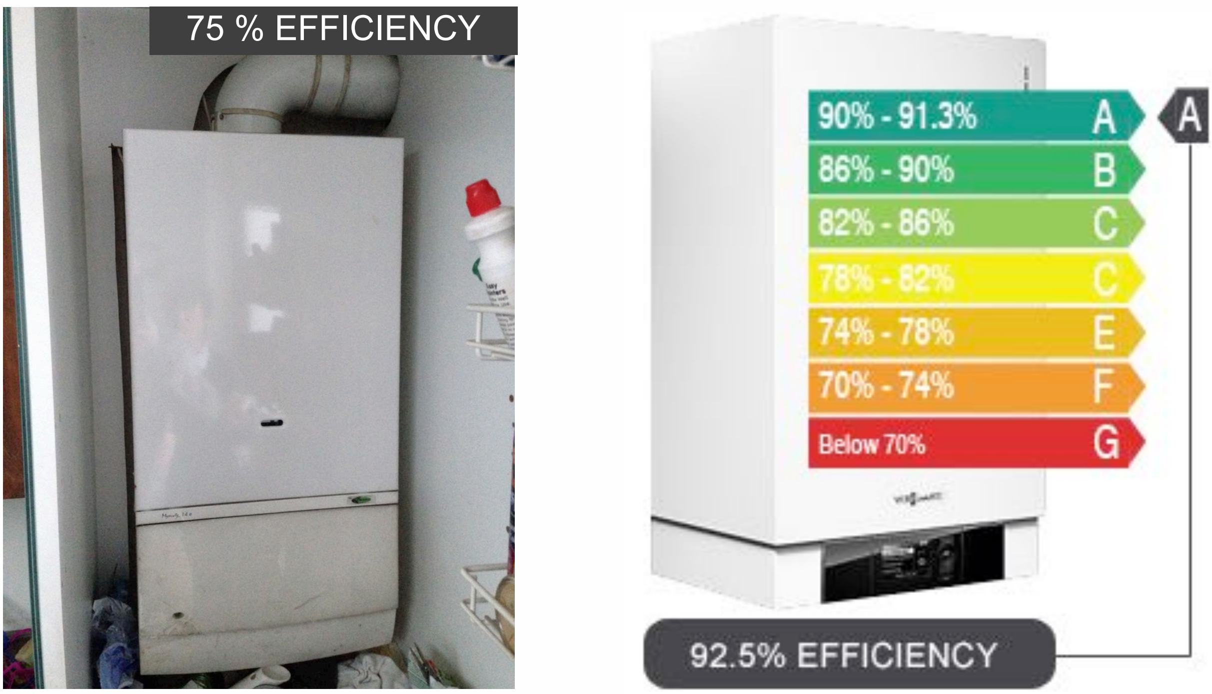


Fig. 4.1   Existing gas boiler (left), proposed replacement condensing boiler (right).

It is assumed that a new 92% efficient gas condensing boiler will cost €2,000 including VAT (supplied & installed). Replacing the existing boiler is calculated using DEAP to reduce annual gas fuel usage by 3,300 kWh per year - a 15% reduction in energy use. The BER (Building Energy Rating) of the dwelling is reduced from 291 kWh/m^2/yr (a D2 rating), to 254 kWh/m^2/yr (a D1 rating). No residual value is assumed for either alternative (both boilers are assumed to be obsolete at the end of the 20 year investment period). SEAI grant subsidies for the boiler replacement are assumed not to be available (currently only available with two or more measures, and only where full boiler controls and interlock are also installed).

No borrowings are required to fund the investment - it is assumed that cash funding for the investment is currently held by the homeowner in a fixed term 'high interest' deposit account earning an average of 3% interest per annum (Central Statistics Office figures give an average interest rate over the last 12 years of 2.0% for consumer deposits, although deposit rates have been at historically low levels in recent years) (CSO, 2015a).

Table 4.1 Assumptions / economic variables used for initial LCCA calculation.

	Assumed value	Rationale
Duration of study	20 years	estimated max. service life of boiler
Discount rate	3%	average deposit rate over last 20 years
General inflation rate	2%	historical average inflation rate / assumption
Fuel inflation	4%	historical gas inflation rate / assumption
Cost of fuel (gas)	€ 0.0681 / kWh	current SEAI gas rates (SEAI 2015b)

Table 4.2 Data / input values used for LCCA calculation for two alternatives.

	A: Keep existing boiler	B: Replace boiler
Annual fuel demand (DEAP)	17,500 kWh/yr	14,200 kWh/yr
Initial capital costs	€0	€2,000

4.2 Results of new boiler LCCA calculation

A summary of the results of the LCCA calculation are shown in table 4.3 below:

Table 4.3 LCCA results - comparative economic analysis for boiler replacement.

ENERGY SAVINGS (PV)	NET SAVINGS (PV)	SIR	AIRR	PAYBACK (Simple)	PAYBACK (Discounted)
€4,982	€2,982	2.49	7.81%	Year 8	Year 9

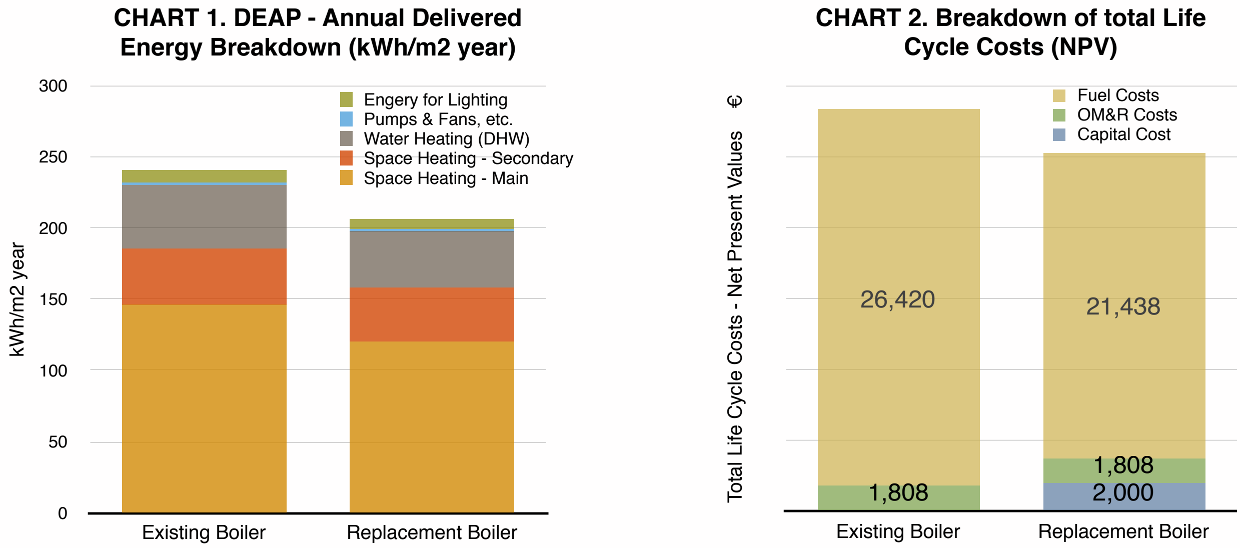


Fig. 4.2 Boiler replacement - energy savings (Chart 1), total LCC (NPV) breakdown (Chart 2).

4.3 Analysis of results - simple LCCA study

A breakdown of the life-cycle costs for the replacement boiler scenario illustrates that in both cases operational fuel costs account for by far the largest proportion of total life cycle costs over the 20 year time span of the study (Fig. 4.2). Based on the initial economic assumptions, the calculation shows that replacing the existing boiler with a new efficient condensing boiler is cost effective - there will be a cost benefit over the assumed study period (20 years). A net saving, or profit on the initial investment will be accrued of €2,982 (NPV). The investment in the new boiler pays for itself after 9 years (Discounted Payback Period), and the Adjusted Internal Rate of Return (AIRR) on the investment is 7.81%.

4.4 Sensitivity analysis

In this simple LCC example, it can readily be seen that the cost effectiveness of the retrofit measure (replacing the existing boiler) is dependant upon the cost data assumptions (how much does the boiler replacement actually cost, and what are the real operational energy cost savings), and also the key economic variables chosen (discount rate, fuel escalation rates, study period and residual values). *Sensitivity analysis* - increasing or decreasing each one of the LCC calculation input variables impacts dramatically on the results:

- An increasing discount rate (interest rate), leads to decreasing net savings from the proposed boiler replacement. Beyond a discount rate of approximately 14%, the boiler replacement becomes no longer cost effective (Figure 4.3 - Graph 1).
- Conversely, an increasing fuel inflation rate, leads to increasing net savings from the proposed boiler replacement. Net savings increase exponentially with increasing fuel inflation.

- The longer the investment period, the greater the net savings calculated for the boiler replacement measure. If however the study period is reduced below 9 years, the measure becomes no longer cost effective (Figure 4.3 - Graph 2).
- Increasing the assumed initial capital costs of the boiler replacement reduces the net savings accrued. If the initial installation costs of the boiler replacement exceeds a limit of €4,900, the measure becomes no longer economic (Figure 4.4 - Graph 3).
- Reducing the heating demand for the boiler (either by reducing heat loss through fabric upgrades, or reduced demand though occupancy behaviour / comfort requirements), reduces fuel use and also the potential net financial savings accrued from a more efficient boiler. The greater the energy saving fabric interventions carried out (e.g. Passive House deep-retrofit), the less cost-effective the systems improvements become (Graph 4).

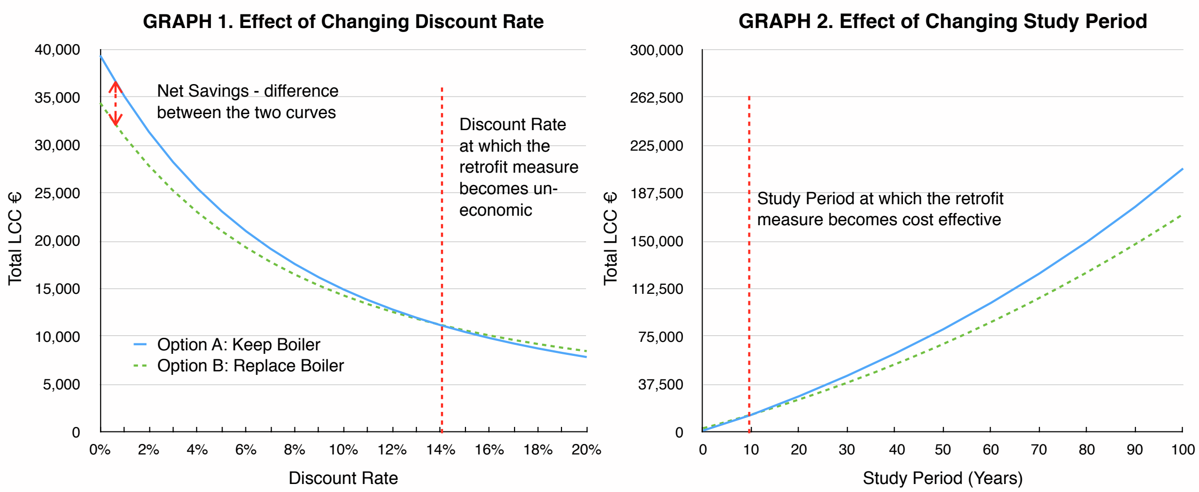


Fig. 4.3 Boiler replacement - sensitivity analysis: impact of changing discount rate (Graph 1), study period (Graph 2), on cost effectiveness of the measure.

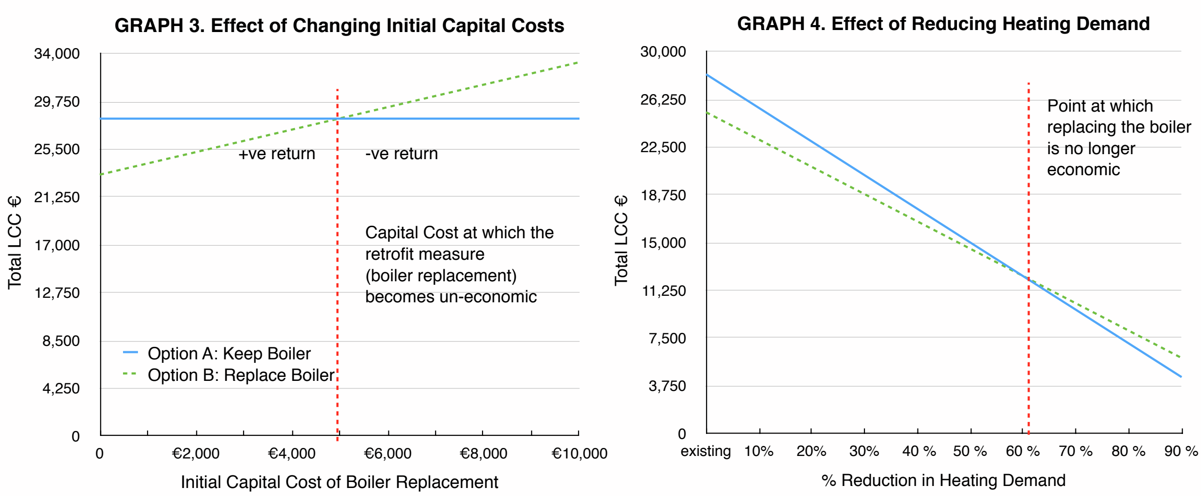


Fig. 4.4 Boiler replacement - sensitivity analysis: impact of changing capital costs (Graph 3), reduced heating demand (Graph 4), on cost effectiveness of the measure.

4.5 Summary of Chapter 4

The main conclusions from this methodology validation chapter are,

- Testing and validation of the LCCA methodology and the BLCC5 software tool has been carried out. The results for a simple LCCA calculation carried out in the BLCC5 Program and a manual (Excel worksheet) formula method correlate.
- For the simple LCCA validation exercise, it was shown that replacing an existing gas boiler with a new more efficient condensing boiler could be cost-effective (the new boiler pays for itself and there is additionally profit generated on the initial investment). However the LCCA result is highly dependent on the assumptions and investment parameters.
- The impact of changing the individual economic variables on the financial appraisal has been clearly demonstrated.

CHAPTER 5: Case Study Building - Galway Passive House Retrofit

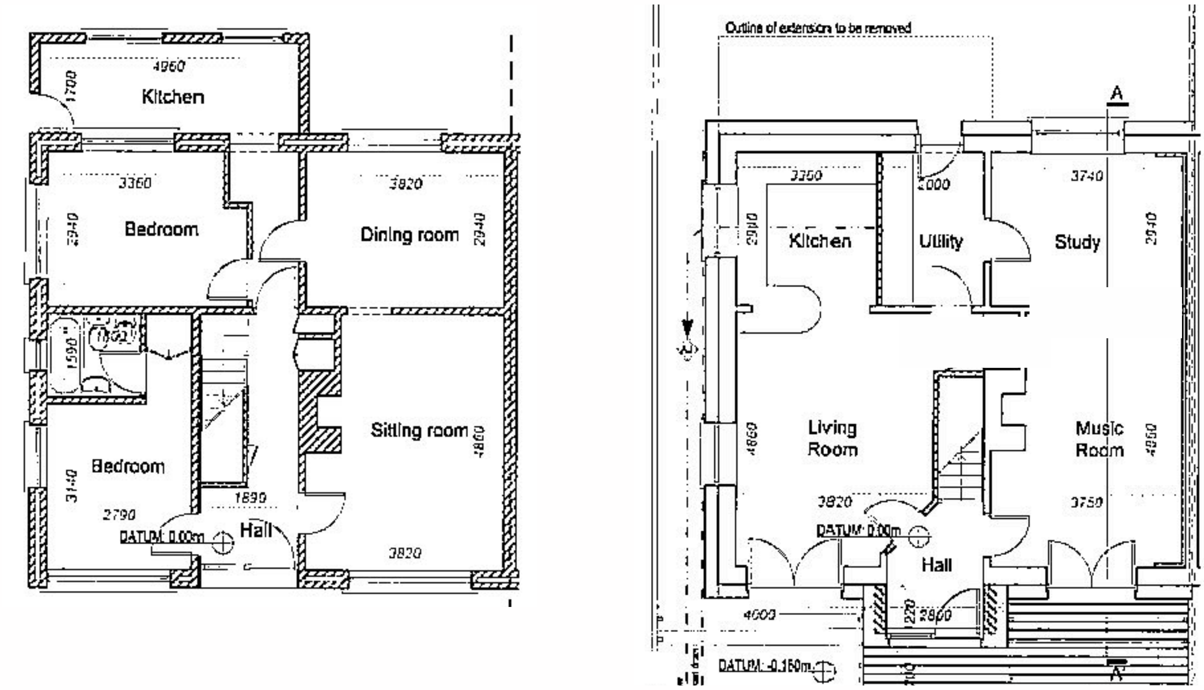
The subject of this Life Cycle Cost Analysis study is a Passive House deep-retrofit of a domestic building located in Galway City, Ireland. Designed by Simon McGuinness Architect, and completed in April 2014, the house is one of only three (at the time of writing) certified Passive House retrofit projects in Ireland (PHI, 2015c). Passive House calculation, design and construction standards were adopted to produce a retrofitted dwelling with a predicted 90% reduction in operational fuel costs, primary energy demand and CO_2 emissions.

Fig 5.1 Case-study building - view of the existing dwelling prior to retrofitting works. (Source: McGuinness, 2014).

5.1 The existing dwelling

The case study building is a typical two-storey speculatively-built semi-detached dwelling, originally constructed in the 1960s and located in a suburban street in the Salthill area of Galway City (Figure 5.1). The existing building when purchased by the current owners in 2013, was laid out with a total internal gross floor area of 148 m^2, including a small (8 m^2) lean-to single storey extension to the rear housing a kitchen and an oil-fired central heating boiler. Regardless of any energy improvement works being considered, the property was also in need of extensive general refurbishment and upgrading works - requiring replacement kitchen and bathroom fittings, repairs/replacement of existing plaster walls and ceiling finishes, replacement of existing floor finishes, as well as comprehensive redecoration. The existing heating, plumbing and electrical services also required complete renewal.

In addition the owners required layout changes and functional alterations to the existing building; demolition of the existing (sub-standard) rear extension, the removal of internal walls to form two large open plan living / work areas on the ground floor, provision of a new front entrance porch / entrance hallway, and a new Utility room. A new repositioned staircase provides greater usable living space (the original entrance hallway / corridor has been incorporated into the main living room). Alterations to the window openings to the front (southern) elevation provide patio doors allowing direct access out onto the south facing front garden.



Original Ground Floor Plan

As Built Ground Floor Plan

Fig 5.2 Original ground floor layout (left), and new reconfigured ground floor layout as built (right). (Source: Simon McGuinness Architect).

5.2 Existing construction and energy performance

The original dwelling was constructed of 300 mm thick externally rendered and internally plastered cavity walls (two layers of 100 mm brick or concrete block, with a 100 mm uninsulated air cavity). The roof construction was a timber trussed roof with concrete interlocking tiles on a felt roofing membrane. The house had an (uninsulated) solid concrete floor and timber joisted intermediate floor, with plasterboard ceilings. Windows and doors were single-glazed and aluminium framed. The almost complete lack of any thermal insulation in the original construction resulted in poor fabric performance, with high U-Values calculated for all wall, roof and solid floor elements (Table 5.1).

Table 5.1 Key energy performance data (DEAP) calculated for existing (pre-retrofit) dwelling.

			Quantity	Unit
Calculation	Method and tools(s)	DEAP v3.2.1 (Spreadsheet Workbook version 0.6) updated 17/12/2014		
	Primary Energy Conversion Factors Used	Oil	1.10	kWh/KWh
		Solid Multi-Fuel	1.10	
		Grid supplied Electrciity	2.37	
Climate	Location	Galway		
	Climate Data	DEAP v3.2.1 Irish climate data (not location specific)		
	Terrain Location	The impact of surrounding buildings has been included (i.e. shelter & shading)		
Geometry	Dwelling Gross Floor Area		148.5	m2
	Living Room Area		16.7	m2
	Total Dwelling Volume		387	m3
	Total External Surface Area		345	m2
Fabric	Fabric U-Values	Wall (cavity walls, 100mm cavity uninsulated)	1.78	W/m2K
		Roof (50mm mineral wool insulation)	2.30	W/m2K
		Floor (uninsulated, solid concerte)	0.84	W/m2K
		Windows (singe-glazed, aluminium)	5.8	W/m2K
		External Doors	3.0	W/m2K
	Thermal Bridging y-value	Thermal Bridging (Default)	0.15	W/m2K
	Fabric Air-tightness	Air Changes per hour at 50 Pascals (Q50)	14	m3/m2.hr
Systems	Ventilation System	Method - Natural Ventilation (no vents - chimney)		
		Heat Recovery Efficiency (with in-use factor)	-	-
		Specific Fan Power (with In-use factor adjst.)	-	-
	Heating system	Fuel	Oil	-
		Generation Efficiency (adjsuted)	75	%
		Distribution / Control Efficiency	78	%
		Secondary Heating Efficiency	30	%
		Secondary Heating Production	10	%
	DHW system	Generation Efficiency (adjusted)	75	%
		Distribution / Control Efficiency	78	%
		Storage losses	1586	kWh year
Setpoints and Scheduele	Temperature setpoint	Living Areas	21	ºC
		Rest of dwelling	18	ºC
	Operation schedules	Schedules defined by DEAP - 07.00h to 9.00h and 17.00h to 23.00h daily. Oct-May		
Energy Use	Heating Energy		213	kWh/m2 year
	Heating Energy Secondary		57	kWh/m2 year
	DHW Energy		36	kWh/m2 year
	DHW Energy (supl.)		10	
	Auxiliary Energy		2	kWh/m2 year
	Lighting Energy		9	kWh/m2 year
Energy Consumption	Total Delivered Energy	Oil	249	kWh/m2 year
		Soild Fuel (Coal / Briquettes / Wood)	57	kWh/m2 year
		Electricity	21	kWh/m2 year
	Primary Energy		388	kWh/m2 year
	BER Rating		F	

Heating of the house was primarily provided by an oil-fired central heating system comprising a (non-condensing) oil-boiler, pressed steel radiators and copper pipe-work. Secondary heating was provided by a solid fuel open fire, with a central fireplace and block-work rendered chimney passing through the roof space and emerging at ridge level. Domestic hot water was provided by a copper cylinder heated indirectly by the oil boiler and with summer electric immersion.

Controls for the heating and hot water systems were rudimentary, with no thermostatic temperature controls, summer bypass (to allow heating of domestic hot water only) or boiler interlock (to prevent boiler from cycling when no heating is required).

In the existing building background room ventilation was not being provided in accordance with current Building Regulations (TGD Part F, 2009 requires permanent wall vents to all habitable rooms and mechanical extraction to kitchen and bathroom spaces) (DECLG, 2009). No air-tightness test was carried out prior to the retrofit works, so the DEAP default value of 14 $m^3/h/m^2$ at 50 Pascals pressurisation is assumed.

A BER assessment of the original dwelling was calculated using DEAP, based on the building geometry, calculated fabric U-Values and services characteristics of the dwelling prior to the retrofit works. The calculated Building Energy Rating (BER) for the existing original building is a F rating, with a Primary Energy Use of 388 $kWh/m^2/yr$ (Table 5.1).

5.3 Design strategy for Passive House retrofit

The retrofit design strategy followed the Passive House design principals of a super-insulated thermal envelope (with insulation continuity to avoid thermal bridging), and an exceptionally high level of structural airtightness combined with an efficient whole house mechanical ventilation system with heat recovery. Carefully sized window openings with low-emissivity triple-glazing maximise passive solar gains, whilst minimising heat losses.

Planning Permission was obtained for the external alterations including enlarged window openings to the south elevation, new front entry porch, external wall insulation and extension to the roof eaves and gable overhang. A comprehensive set of architectural plans, details, specification and schedule of works was then prepared by the architect to allow tendering of the works by a pre-selected building contractor, who notably had no previous experience of building to the Passive House standard or specific expertise in airtightness measures.

The specification documents included a requirement for air-tightness testing at specific stages during the construction (3 blower door tests carried out by an independent NSAI approved tester), and a final measured performance criteria of achieving the 0.6 ach^{-1} (at 50 Pascals pressurisation) required to meet the (full) Passive House certification criteria.

Fig 5.3 Achieving airtightness: (Top) First floor ceiling removed and airtight membrane installed below the existing roof joist, with battens to form service cavity, membrane taped to internal wet plaster layer. (Middle) Ground floor ceilings removed and internal plaster layer patched between floor joists, joists ends taped at wall junction. (Bottom) Airtight sealing tape to junction of all external walls and new concrete floor slab. Passive House certified windows, taped at all junctions to form continuous seal with internal wet plaster layer. (Source: McGuinness, 2014).

5.4 Passive House retrofit - fabric upgrade works

For the Passive House retrofit of the dwelling, the main fabric improvements included pumped cavity fill insulation (100 mm Polystyrene) and external wall insulation (200 mm mineral wool with silicate render) added to the existing external cavity walls, with the external wall insulation continued below the ground externally down to the existing foundations (200mm extruded polystyrene). 400 mm of mineral wool insulation was installed to the existing roof (along plane of ceiling), with additional rigid PIR and foam insulation installed between the rafters at eaves level, to ensure continuity of the insulation layer and thermal bridge free junctions, whilst still maintaining adequate ventilation to the roof space.

At ground level, the existing floor slab was completely removed, the ground excavated, and a new reinforced concrete slab installed incorporating 200 mm of extruded polystyrene insulation. This included vertical perimeter insulation at edges, again to ensure continuity of the insulation layer and to limit thermal bridging. All windows and doors were replaced with Passive House certified triple glazed thermally broken doors and windows, with overall window U-Values (takes into account both glazing and frame) of 0.9 - 0.96 W/m^{2}K.

An essential element of the Passive House standard, indeed perhaps its principal defining characteristic over other low-energy design standards, is the fundamental requirement to achieve a very high level of structural airtightness within the enclosing building envelope, combined with a highly efficient mechanical ventilation system with heat recovery (to recover heat losses within extracted air that would otherwise be wasted). The case study project demonstrates the possibility of the achievement of extraordinary high levels of airtightness within retrofitted dwellings, well and above the current minimum targets even for new build contained within current Building Regulations. The case study retrofit achieved an air-tightness Q50 value of approximately 0.4 m^3/h/m^2 (at 50 Pascals pressurisation), whereas the current minimum 'best-practice' standard required for new build under the current Irish Building Regulations is nearly 20 times this value at 7 m^3/h/m^2 (DECLG, 2011).

Achieving such a high level of airtightness, and in particular to an existing (retrofitted) building is no mean feat. The levels of airtightness were achieved by careful design, planning, and implementation on site of a rigorous airtightness strategy, which included: (1) removal of the existing (redundant) chimney completely down to foundation level, (2) maintaining (and repairing) a continuous, completely intact internal wet plaster layer on the external walls from the Ground floor slab up to the first floor ceiling, (3) no chased services installed in the external walls of any kind (e.g. electrical conduits or pipes), (4) an airtight membrane installed to the First floor ceiling, and sealed to the plaster walls with airtight tape, (5) all windows and doors are Passive House certified air-tight units with double seals and taped at all edges to wall reveals and floors under the plaster layer, and (6) all necessary openings and service penetrations through the external envelop fully sealed using proprietary air-tight tapes, mastic and grommets (Figure 5.3) (McGuinness, 2014).

5.5 Retrofit services strategy - heating, domestic hot water and ventilation

The Passive House standard is a 'fabric-first' low-energy strategy - focusing on thermal fabric measures to achieve an ultra-low space heating demand in the first instance. The high levels of super-insulation and airtightness, and optimisation of passive gains in the retrofitted dwelling give rise to near-zero space heating requirement.

The residual space heating and domestic hot water demands of the dwelling are met by a 6.7 kW air to water heat pump unit, with a coefficient of performance of 4.17 (4.17 kWh of heat is produced for every kWh of electricity used). Two wall mounted low-temperature radiators on the ground floor, and a single bathroom towel-radiator on the first floor provide space heating, together with a small post-air heater to the mechanical ventilation system.

The MVHR unit is located in the Utility room with flexible air supply and extract ducting to all the rooms. In summer the unit can run in bypass mode (without heat recovery) to help with cooling. The MVHR system provides for recirculation of heat around the whole house to achieve a constant 20º C to all rooms (there is no zoning or scheduling in Passive Houses - the standard aims to achieve a constant 20º C comfort temperature in all rooms, at all times). Domestic hot water for the bathrooms and kitchen is provided via a factory insulted hot water storage tank also heated by the heat pump.

The retrofit fabric and systems upgrades described above have resulted in a retrofitted dwelling with a A2 BER rating, with a calculated total primary energy demand of of 43 kWh/ m^2/yr. (Table 5.2).

Fig. 5.4 Case-study building - existing dwelling after retrofitting works - view from street.

Table 5.2 Key energy performance data (DEAP) calculated for Passive House retrofitted dwelling

			Quantity	Unit
Calculation	Method and tools(s)	DEAP v3.2.1 (Spreadsheet Workbook version 0.6) updated 17/12/2014		
	Primary Energy Conversion Factors Used	Oil	1.10	kWh/KWh
		Solid Multi-Fuel	1.10	
		Grid supplied Electrciity	2.37	
Climate	Location	Galway		
	Climate Data	DEAP v3.2.1 Irish climate data (not location specific)		
	Terrain Location	The impact of surrounding buildings has been included (i.e. shelter & shading effects)		
Geometry	Dwelling Gross Floor Area		140	m2
	Living Room Area		25.9	m2
	Total Dwelling Volume		365	m3
	Total External Surface Area		330	m2
Fabric	Fabric U-Values	Wall	0.12	W/m2K
		Roof	0.11	W/m2K
		Floor	0.17	W/m2K
		Windows	0.96	W/m2K
		External Doors	0.90	W/m2K
	Thermal Bridging y-value	Thermal Bridging	0.08	W/m2K
	Fabric Air-tightness	Air Changes per hour at 50 Pascals (Q50)	0.40	m3/m2.hr
Systems	Ventilation System	Method - Balanced whole-house mechanical ventilation with heat recovery		
		Heat Recovery Efficiency (with In-use factor adjst.)	75	%
		Specific Fan Power (with In-use factor adjst.)	1.2	W/(l/s)
	Heating system	Fuel	Electrcity	-
		Generation Efficiency (adjsuted)	292	%
		Distribution / Control Efficiency	102	%
		Secondary Heating Efficiency	-	-
		Secondary Heating Production	-	-
	DHW system	Generation Efficiency (adjusted)	292	%
		Distribution / Control Efficiency	102	%
		Storage losses	662	kWh year
Setpoints and Schedueles	Temperature setpoint	Living Areas	21	ºC
		Rest of dwelling	18	ºC
	Operation schedules	Schedules defined by DEAP - 07.00h to 9.00h and 17.00h to 23.00h daily. Oct-May		
Energy Use	Heating Energy		0	kWh/m2 year
	Heating Energy Secondary		0	kWh/m2 year
	DHW Energy		8	kWh/m2 year
	Auxiliary Energy		5	kWh/m2 year
	Lighting Energy		5	kWh/m2 year
Energy Consumption	Total Delivered Energy	Oil	-	-
		Soild Fuel (Coal / Briquettes / Wood)	-	-
		Electricity	18	kWh/m2 year
	Primary Energy		43	kWh/m2 year
	BER Rating		A2	

Table 5.3 Key energy performance data (DEAP) calculated for B3 'Shallow Retrofit' alternative

			Quantity	Unit
Calculation	Method and tools(s)	DEAP v3.2.1 (Spreadsheet Workbook version 0.6) updated 17/12/2014		
	Primary Energy Conversion Factors Used	Oil	1.10	kWh/KWh
		Solid Multi-Fuel	1.10	
		Grid supplied Electrciity	2.37	
Climate	Location	Galway		
	Climate Data	DEAP v3.2.1 Irish climate data (not location specific)		
	Terrain Location	The impact of surrounding buildings has been included (i.e. shelter & shading)		
Geometry	Dwelling Gross Floor Area		148.5	m2
	Living Room Area		16.7	m2
	Total Dwelling Volume		387	m3
	Total External Surface Area		345	m2
Fabric	Fabric U-Values	Wall (EWI + cavity fill)	0.21	W/m2K
		Roof (300mm mineral wool insulation)	0.16	W/m2K
		Floor (uninsulated, solid concerte)	0.84	W/m2K
		Windows (double-glazed, low-e glass)	1.6	W/m2K
		External Doors	2.0	W/m2K
	Thermal Bridging y-value	Thermal Bridging (Estimated)	0.30	W/m2K
	Fabric Air-tightness	Air Changes per hour at 50 Pascals (Q50)	14	m3/m2.hr
Systems	Ventilation System	Method - Natural Ventilation - room vents, mech extract from wet rooms		
		Heat Recovery Efficiency (with in-use factor)	-	-
		Specific Fan Power (with In-use factor adjst.)	-	-
	Heating system	Fuel	Oil	-
		Generation Efficiency (adjsuted)	92	%
		Distribution / Control Efficiency	102	%
		Secondary Heating Efficiency	70	%
		Secondary Heating Production	10	%
	DHW system	Generation Efficiency (adjusted)	92	%
		Distribution / Control Efficiency	102	%
		Storage losses	662	kWh year
Setpoints and Scheduele s	Temperature setpoint	Living Areas	21	°C
		Rest of dwelling	18	°C
	Operation schedules	Schedules defined by DEAP - 07.00h to 9.00h and 17.00h to 23.00h daily. Oct-May		
Energy Use	Heating Energy		80	kWh/m2 year
	Heating Energy Secondary		12	kWh/m2 year
	DHW Energy		18	kWh/m2 year
	DHW Energy (supl.)		0	
	Auxiliary Energy		2	kWh/m2 year
	Lighting Energy		5	kWh/m2 year
Energy Consumption	Total Delivered Energy	Oil	98	kWh/m2 year
		Soild Fuel (Coal / Briquettes / Wood)	12	kWh/m2 year
		Electricity	7	kWh/m2 year
	Primary Energy		136	kWh/m2 year
	BER Rating		B3	

5.6 Case study - capital investment costs of Passive House retrofit

Initial capital investment costs for the case study Passive House retrofit have been compiled and assessed in accordance with the methodology described in Chapter 3. The total initial capital costs (total project costs) for the case study are calculated in the amount of €169,580 including VAT, professional fees and ancillary costs. Separating out the costs of the Passive House (energy-saving) measures, from the general refurbishment and alteration works, gives costs is the order of €110,510 (€778 per m^2), representing 65% of the total project costs. A breakdown of the calculated Passive House retrofit investment costs is shown in Table 5.6.

5.7 Retrofit alternatives - Upgrade Services, and B3 'Shallow Retrofit'

In order to assess the Passive House life cycle costs in comparison with less intensive (and less costly) interventions, two alternative notional retrofit scenarios have additionally been examined: (1) The existing pre-retrofit dwelling with only systems upgrades (space heating & DHW) - estimated total cost €12,500, and (2) a 'shallow retrofit' involving systems upgrades as well as more conservative fabric upgrades (new double-glazed windows, external wall and roof insulation, no floor replacement or insulation), and the provision of a solar hot water system (roof mounted solar panel). Energy performance data for this alternative, calculated to have a B3 BER rating (136 kWh/m^2/yr), is set out in Table 5.3. The initial capital costs of the B3 'Shallow Retrofit' are estimated to be €57,441 (€410 per m^2) - approximately half the cost of the Passive House retrofit. A breakdown of estimated costs for the B3 'Shallow Retrofit' alternative is set out in Table 5.7.

Table 5.4 Total initial capital investment costs estimated for the four alternatives

	1. Base 'Do Nothing'	2. Systems Upgrade	3. B3 'Shallow Retrofit'	4. Passive House
Capital investment (estimate)	€0	€12,500	€57,441	€110,510

Table 5.5 Energy demand (Delivered Energy) - kWh/yr calculated for four alternatives

	1. Base 'Do Nothing'	2. Systems Upgrade	3. B3 'Shallow Retrofit'	4. Passive House
Space heating - primary	31,768	25,053	11,170	0
Space heating - secondary	8,420	8,573	1,622	-
DHW - primary	5,354	4,115	2,450	1,173
DHW - supplementary	1,471	-	-	-
Auxiliary electrical	230	230	335	671
Electrical lighting	1,326	626	634	634
Total delivered energy	48,568	38,598	16,211	2,478
BER (Building Energy Rating)	**F**	**E1**	**B3**	**A2**

Table 5.6 Cost breakdown for Passive House energy retrofit measures

Item	Cost €	Notes
Preliminaries (overheads, insurance etc.)	2,050.88	Allocated on pro-rata basis between PH & Non-PH works
Scaffolding	3,016.00	Scaffolding reqd. primarily for EWI & roof alterations / Insulation
External demolitions and disposal	1,967.68	Removal windows & sills, rw goods, perimeter trench, chimney
Internal demolitions and disposal	5,614.60	Break up and remove floor slab, remove ceilings, partition ends
New concrete ground floor slab (insulated)	7,649.33	Replacement ground floor required to install floor insulation
New blockwork	728.83	Altering window opes to north elevation (reduces heat losses)
1st fix carpentry	3,458.00	Altering or replacing internal stud walls to install airtight layer
Airtightness - windows	1,125.28	Airtight tape & mastic
Airtightness - first floor ceiling membrane	1,430.00	Airtight membrane to 1st floor ceiling, taped junctions, battens
Airtight - testing	546.00	3 Blower-door tests by NSAI approved airtightness tester
Pumped insulation to cavity walls	939.64	100mm blown polystyrene beaded insulation
Insulation - external wall insulation	19,349.41	200mm Rockwool & mineral render, 200mm XPS below ground
Insulation - roof / ceiling insulation	4,565.60	400mm mineral wool insulation, PIR insulation + foam to eaves
Electrical installations	350.00	Extra wiring and controls for MVHR, low-energy bulbs.
Heating (heat pump) & DHW installations	13,809.60	Assumes 100% of total costs of installation as PH cost
New windows and doors, & new metal sills	8,575.00	Assumes existing original windows & doors were servicable
MVHR system - supply & installation	5,203.17	E/O costs - in lieu of standard wall vents & extract fans
Thermal bridge elimination	1,508.00	Perimeter edge insulation, roof eaves detail etc.
Internal plastering & patching.	3,978.00	Repairs / patching to internal plaster to achieve airtight layer
Joinery – internal joinery allowance	1,110.72	New skirting, battens etc. required after plastering at joist ends
Insulated cover to attic access hatch	285.00	Airtight seal & insulated cover over standard STIRA
Roof – re-tiling, eaves and barge extensions	3,224.00	Required due to EWI & eaves insulation, chimney removal.
New rainwater goods	1,651.10	Required due to EWI & altered roof eaves
External works and finishes	1,040.00	Making good conc. screeds around foundation trenches (EWI)
Construction costs sub-total	93,175.84	
Add for VAT @ 13.5%	12,578.74	Portion of VAT reclaimable through HRI scheme (see below)
Construction costs including vat @ 13.5%	105,754.58	
Ancillary & indirect costs:		
Professional fees - architect (Incl. VAT)	8,415.12	Allocated on pro rata basis between PH / Non PH Costs
Planning application costs & charges	290.00	Allocated on Pro rata basis between PH / Non PH
Passive House certification	1,500.00	Cost of quality assurance / certification
SEAI grants - rebate	- 4,700.00	BEH grant for EWI, roof insulation, boiler + controls
HRI scheme - VAT rebate	- 2,349.00	Assumes contractor / client eligible to claim back VAT
Relocation costs (2 months rent @ €800 pm)	1,600.00	Allocated on pro rata basis between PH / Non PH
TOTAL PASSIVE HOUSE COSTS	€110,510.70	(Extra-over costs of Passive House / energy retrofit measures)
COSTS PER m2 (141m2)	€ 778.24	

Table 5.7 Cost breakdown for B3 'Shallow Retrofit' energy retrofit measures

Item	Cost €	Notes
Preliminaries (overheads, insurance etc.)	1,467.75	Reduced Preliminaries (reduced contract period)
Scaffolding	2,450.00	Scafolding for EWI, limited roof alterations (reduced time)
External demolitions and disposal	857.40	Removal of windows, rw goods, (chimney retained)
Internal demolitions and disposal	535.86	Minimal internal energy refurbishment works
New concrete ground floor slab (insulated)	-	Existing floor slab retained
Blockwork.	-	N/A
1st Ffix carpentry	-	No airtightness measures carried out
Airtightness - windows	-	No airtightness measures carried out
Airtightness - first floor ceiling membrane	-	No airtightness measures carried out
Airtightness - testing	-	No airtightness measures carried out
Pumped insulation to cavity walls	939.64	100mm blown polystyrene beaded insulation
Insulation - external wall insulation	17,450.00	150mm EPS & mineral render
Insulation - roof / ceiling insulation	3,365.60	300mm mineral wool insulation, PIR insulation + foam to eaves
Electrical installations	350.00	Extra wiring and controls for MVHR, low-energy bulbs.
Heating & DHW installations	8,650.00	Standard condensing oil boiler & rads, controls, zoning etc.
New windows and doors, & new metal sills	6,730.00	Standard double-glazed uPVC replacement windows
Ventilation (extract fans & vents)	578.13	Standard 'hit & miss' wall vents & extract fans from wet areas
Solar hot water panel (4m2)	4,800.00	4m2 solar panel, solar station & dual cylinder
Internal plastering & patching.	-	No airtightness measures carried out
Joinery – internal joinery allowance	-	No airtightness measures carried out
Insulated cover to attic access hatch	285.00	Insulated cover over standard STIRA
Roof – re-tiling, eaves and barge extension	1,978.00	Required due to EWI & eaves insulation
New rainwater goods	1,651.10	Required due to EWI & altered roof eaves
External works and finishes	1,040.00	Making good conc. screeds around foundation trenches (EWI)
Construction costs sub-total	53,128.48	
Add for VAT @ 13.5%	7,172.34	Portion of VAT reclaimable through HRI scheme (see below)
Construction costs including VAT @ 13.5%	60,300.82	
Ancillary & indirect costs:		
Professional fees - architect (incl. VAT)	4,800.00	Allocated on pro-rata basis between energy & incidental works
Planning application costs & charges	290.00	Allocated on pro-rata basis between energy & incidental works
Passive House certification	-	N/A
SEAI grants - rebate	- 6,000.00	BEH grant for EWI, roof insulation, SHW panel, boiler + controls
HRI scheme - VAT rebate	- 2,349.00	Assumes contractor/client eligible to claim back VAT (pro-rata)
Relocation costs (2 weeks rental)	400.00	Internal retrofit works limited to heating system replacement
TOTAL ENERGY RETROFIT COSTS	€57,441.82	(Extra-over project costs of B3 'Shallow Retrofit' measures)
COSTS PER m2 (141m2)	€ 410.30	

5.8 Summary of Chapter 5

The main conclusions from this case study chapter are,

- Energy analysis of the case study dwelling using DEAP calculates that the Passive House retrofit standard applied has achieved an A2 BER rating (43 $kWh/m^2/yr$). This compares with an F rating (388 $kWh/m^2/yr$) for the original (pre-retrofit) dwelling, representing an estimated 90% reduction in primary energy demand.
- Total delivered energy (operational fuel use as would appear on utility bills) in the Passive House dwelling is calculated at 2,478 kWh per year, compared to 48,568 kWh per year calculated for the original dwelling. This represents an estimated 95% reduction in operational energy demand.
- The majority of the energy reductions have been achieved through fabric improvement measures - super insulation (continuous to all floor, walls and roof elements), triple glazed Passive House windows, and air-tightness (combined with heat recovery from ventilation).
- With a calculated near-zero space heating demand for the Passive House dwelling, the method of space heating and system efficiency becomes less critical. The heat pump installed is primarily being used to provide domestic hot water.
- An analysis of the total project costs has been carried out based on the architect’s Final Account for all the works. Isolation of the Passive House energy efficiency retrofit costs, separated from incidental refurbishment costs was carried out in accordance with the methodology outlined earlier.
- The total costs of the Passive House retrofit is estimated to be €110,510. A less intensive 'Shallow Retrofit' scenario (to B3 BER rating), is estimated to incur approximately half the initial capital investment (€57,441).

CHAPTER 6: Results and Analysis

6.1 Comparative results of operational energy use, fuel cost and CO_2 emissions

A comparison of the delivered energy, CO_2 emissions and operational energy costs for each of the four alternatives (calculated using DEAP software) is shown in Fig. 6.1. The results indicate an estimated 95% reduction in total delivered energy and a 90% reduction in both CO_2 emissions and total energy costs achieved in the Passive House deep-retrofit over the original base-line (pre-retrofit) dwelling. Lesser reductions are achieved with the intermediate retrofit scenarios: just upgrading the existing heating system and controls is predicted to reduce total energy use, CO_2 emissions and energy costs by approximately 16%. Whilst the B3 'Shallow-Retrofit' alternative is estimated to deliver reductions of approximately 70% over the baseline dwelling.

To offset the higher primary energy and carbon emissions associated with the B3 'Shallow-Retrofit' alternative, down to a similar level as the Passive House retrofit standard would require a photovoltaic array, or some other form of renewable energy source, capable of delivering approximately 5,500 kWh per year. This would require for example, a south facing photovoltaic array of some 45-50 m^2 (enough to entirely fill the existing southern roof facade of the case study dwelling), with an approximate estimated capital installation cost in the region of €45-50,000, and with an estimated service life for the photovoltaic system of 25 years (Famuyibo, 2012; SEAI, 2015c).

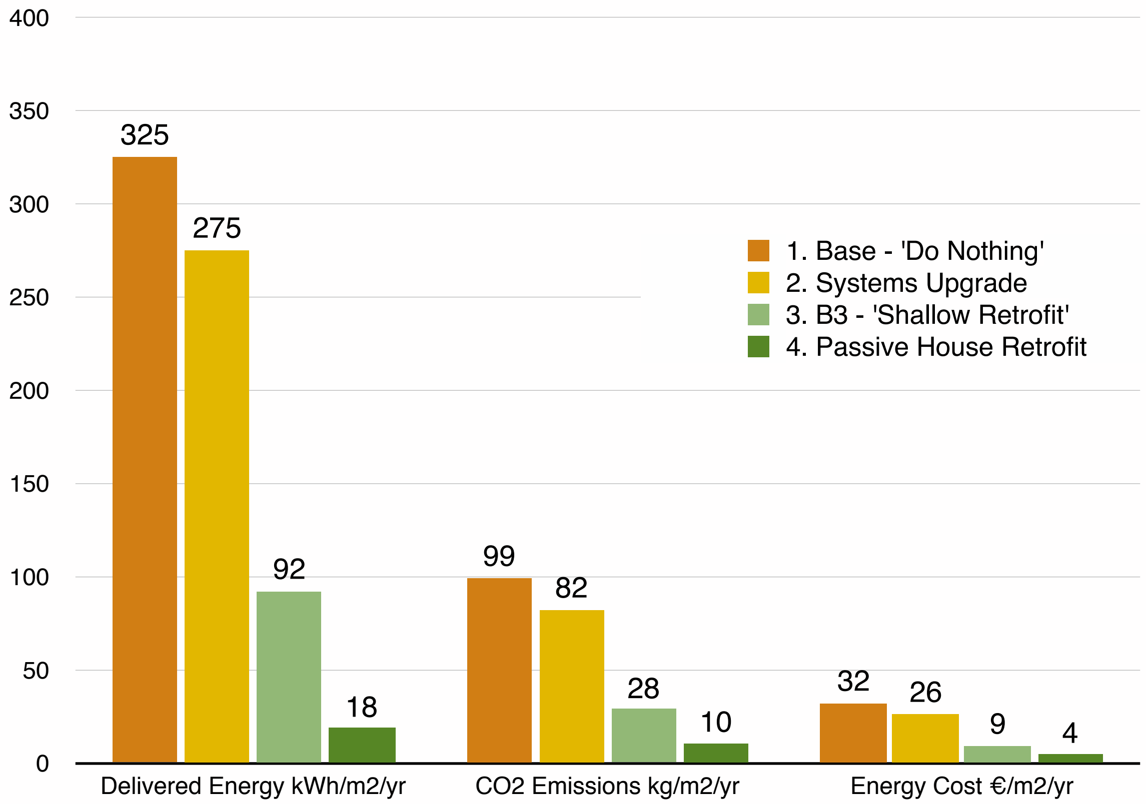


Fig. 6.1 Comparative delivered energy, CO_2 emissions, and energy costs for retrofit alternatives.

6.2 Results of calculated vs. actual (measured) operational energy use

In the original (pre-retrofit) dwelling, the dominant energy demand is from space heating (83%), followed by domestic hot water (14%) (Fig 6.2). The combined space heating and hot water energy demand in the pre-retrofit dwelling is calculated (in DEAP) to be in excess of 47,000 kWh per annum. In the (as built) Passive House dwelling, this demand is reduced to 1,243 kWh per annum (over 97% reduction), with space heating almost entirely met by passive gains (DEAP in fact calculates a zero space heating demand).

A comparison of space heating and hot water energy demand calculated in the DEAP software, with actual in-use monitoring shows a reasonably close alignment between predicted and actual energy usage for the Passive House case study dwelling (Fig 6.3). Measurements over a 12 month period of the hours in use of the heat pump used for space heating and domestic hot water recorded a total annual energy consumption (electricity) of 1,072 kWh per annum, as compared to the (DEAP) calculated estimate of 1,242 kWh per annum. There is some under-estimation of the space heating demand in DEAP, (attributable to DEAP's standard heating set-point temperatures and scheduling assumptions), and conversely a slight over-estimation of the domestic hot water demand (again attributable to occupancy default values - the DEAP model assumes 3.92 occupants, when in reality there are only two).

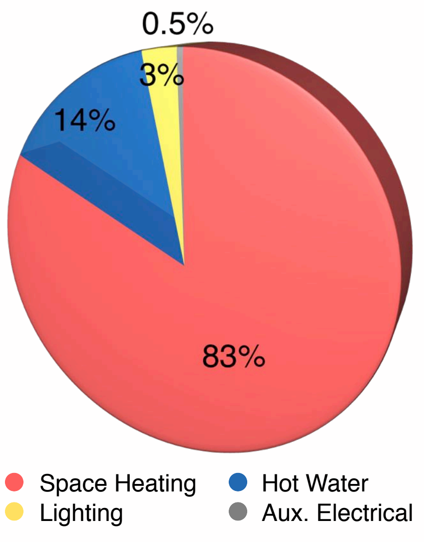


Fig 6.2 Energy breakdown - existing Base

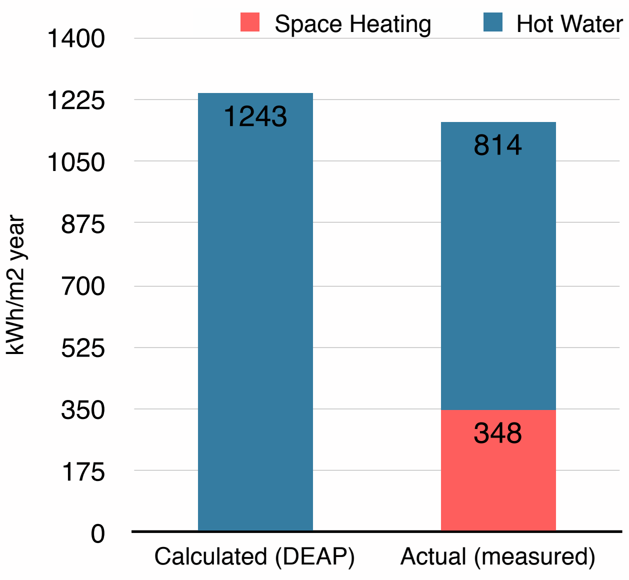


Fig 6.3 PH energy breakdown, calculated vs. actual

Actual monitored energy use for the original (pre-retrofit) dwelling was not available for the case study, but there is some suggestion that in such a highly energy inefficient dwelling (BER F Rating), the actual energy consumption used for space heating may be significantly over-estimated by energy analysis tools such as DEAP or PHPP, in some instances by as much as 50%. (IEE, 2014; Scheer, Clancy & Ní Hógáin, 2012; Versele *et al* 2009).

Such a differential may well be explained by occupancy patterns and behaviour, and a tendency in 'real life' for occupants of poorly insulated and thermally in-efficient dwellings to under-heat dwellings, or particular rooms within a dwelling below the actual comfort conditions assumed by the energy analysis model.

Clearly the impact of such a discrepancy would be to over-estimate the 'real' operational energy costs savings that are actually being achieved by the Passive House retrofit and therefore reduce its (relative) cost effectiveness. The impact of such a performance gap (between calculated and actual energy savings) is assessed and discussed in the sensitivity analysis results at the end of this chapter.

6.3 Results of LCCA for the Passive House retrofit

Life Cycle Cost calculations were carried out for the Passive House case study retrofit using the BLCC5 software. The initial calculations assumed a study period of 30 years and a discount rate of 4% (the assumed maximum term and long term variable interest rate for a secured mortgage loan). It is assumed that the refurbishment works will have a minimum design lifespan of 50 years, and that there will therefore be a (pro-rata) remaining residual value for the works of 40% of their original costs (NPV) at the end of the study period. General inflation is assumed at 2%, and a fuel escalation rate of 4% (all fuels).

The LCCA computes total (present value) life-cycle costs for the Passive House retrofit to be €112,924. This includes a NPV deduction of €24,689 in respect of the remaining residual value for the retrofit works. A comparative analysis between the Passive House and the original 'Do-nothing' base case dwelling shows that the Passive House measures are cost effective, with predicted Net Savings (NS) in the amount of € 34,626, a Savings-to-Investment Ratio (SIR) of 1.4, and an Adjusted Internal Rate of Return (AIRR) of 5.18%. Simple Payback occurs in year 18, and Discounted Payback after 28 years (Table 6.1).

Table 6.1 LCCA - comparative economic analysis for Passive House retrofit (4**%** discount rate)

TOTAL LCC (PV)	NET SAVINGS (PV)	SIR	AIRR	PAYBACK (Simple)	PAYBACK (Discounted)
€112,924	€34,626	1.4	5.18%	18 yrs	28 yrs

6.4 Retrofit alternatives - comparative results of LCCA

Life Cycle Cost calculations were carried out for all the four retrofit scenarios outlined previously. A comparison of the total NPV for the four retrofit scenarios (1. Base 'Do-nothing', 2. Systems Upgrade (Heating & DHW), 3. B3 'Shallow Retrofit', and 4. Passive House Retrofit - as built) is shown in Table 6.2.

Table 6.2 Results of LCCA calculations for four project alternatives.

	INITIAL CAPITAL COSTS (PV)	TOTAL LCC (PV)	NET SAVINGS (PV)	PAYBACK (Discounted)
1. Base - 'do nothing'	€0	€147,550	-	-
2. Upgrade Systems	€12,500	€131,210	€16,341	15 yrs
3. B3 'Shallow Retrofit'	€57,441	€101,241	€46,309	19 yrs
4. Passive House Retrofit	€110,510	€112,924	€34,626	28 yrs

Firstly it can be seen that all of the retrofit measures have lower total Life Cycle Costs than the 'Do-nothing' base dwelling - meaning they are all cost effective, or 'profitable' over the 30 year study period. Doing nothing is actually the most expensive option. On a purely financial basis, the LCCA suggests that the B3 'Shallow Retrofit' scenario is the most cost-optimal of all the alternatives considered - the LCCA calculates it to have the lowest overall Life Cycle Costs, generating the highest Net Savings (€46,309). This is followed in second place by the Passive House retrofit with Net Savings of €34,626. The fact that the alternative involving only an upgrade of the heating system produces the lowest Net Savings (€16,341) despite having much lower initial capital costs and the fastest Payback Period (15 years), illustrates the point that Payback is a poor indicator of overall cost effectiveness, and moreover the principle in retrofit economics of 'spending more to save more'.

6.5 Breakdown of life cycle costs

A breakdown of the different elements of total life cycle costs for each alternative is shown in Fig 6.4. Costs are divided into Operational Energy Costs, Maintenance and Repair Costs (OM&R) and Initial Capital Costs (less PV residual values). It can be seen that in the (pre-retrofit) original dwelling, Operational Energy Costs are by far the dominant Life Cycle cost, compared with the Passive House where Initial Capital Costs become the most significant cost.

6.6 Sensitivity analysis

It has already been discussed previously that there are many input variables and economic assumptions attached to LCCA that determine the output results. Varying each one of the LCCA input variables can impact dramatically on the results. It follows that there are risks and uncertainty inherent within any economic analysis, so the LCCA methodology adopted by this study uses sensitivity analysis to assess this uncertainty. Individual inputs and economic variables are adjusted, one at a time, and the LCCA recalculated. In this way the relative impact of individual variables is assessed.

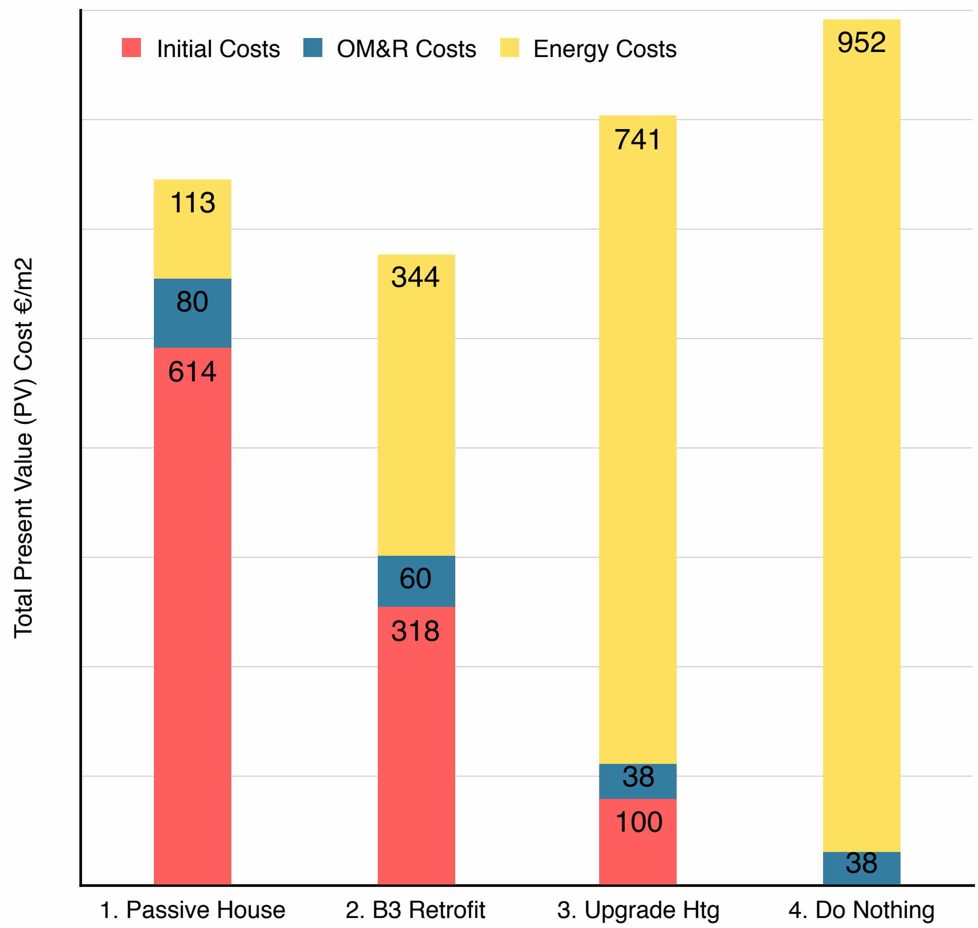


Fig. 6.4 Breakdown of elements of total life-cycle costs for project alternatives (present value costs)

6.6.1 Effect of changing discount rate

The discount rate selected is perhaps the most critical factor in LCCA calculations, and hence the cost effectiveness of the energy retrofitting measures assessed. Low discount rates produce higher net savings, encouraging higher initial investment costs, whereas an increasing discount rate, leads to decreasing present value future savings. The graph below shows the effect of an increasing discount rate for the case study LCCA (Fig 6.5).

With a discount rate at or below 2.7%, the Passive House retrofit becomes more cost effective (greater total net savings), than the cheaper B3 'Shallow Retrofit' alternative. The net savings (profits) generated by the Passive House retrofit increase to over €200,000 with a 0% discount rate, whilst above a discount rate above 5.6% the Passive House retrofit measures become no longer cost effective (negative Net Present Values).

If a discount rate for the calculation of 7% is assumed (as in Pountney *et al*, 2014), the Passive House measures are no longer cost effective, with a predicted loss on the investment in the amount of €19,420. The Savings-to-Investment Ratio (SIR) is less than 1.0, and the Adjusted Internal Rate of Return (AIRR) is less than the discount rate. Discounted Payback is never reached during the study period (Table 6.3).

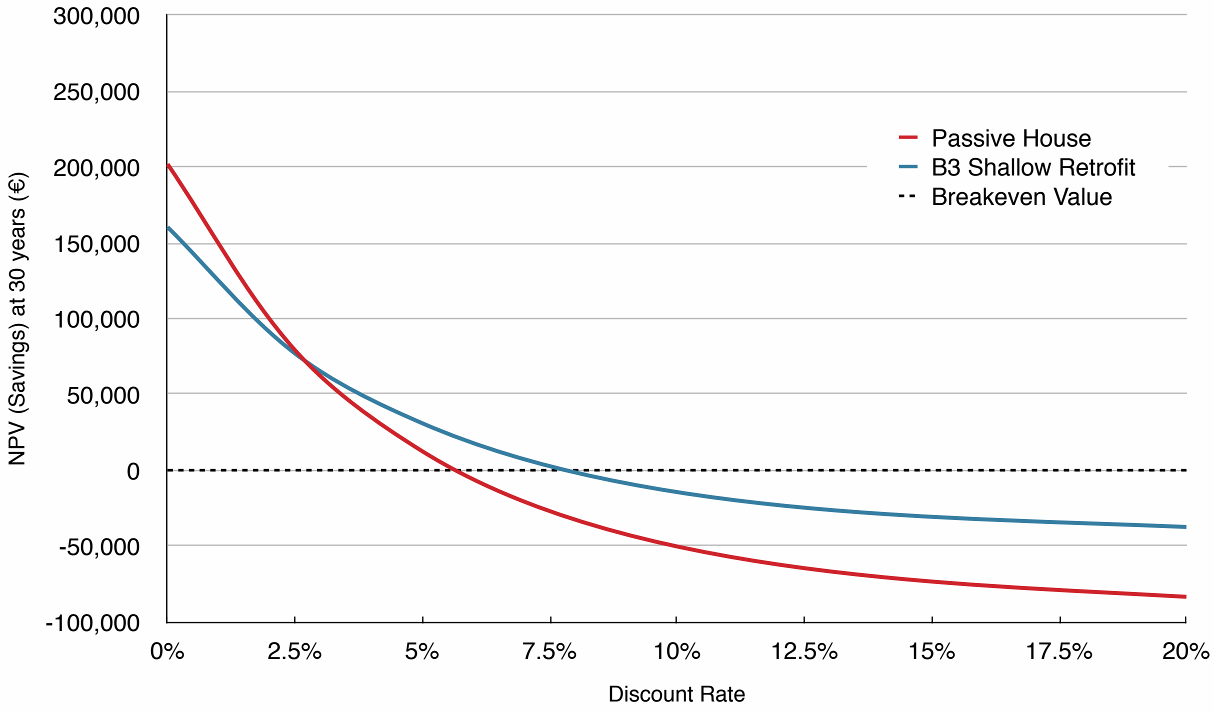


Fig. 6.5 Effect of discount rate on NPV (cost savings).

Table 6.3 LCCA - comparative economic analysis for Passive House retrofit - **7%** discount rate

TOTAL LCC (PV)	NET SAVINGS (LOSS)	SIR	AIRR	PAYBACK (Simple)	PAYBACK (Discounted)
€117,539	-€19,420	0.81	6.23%	18 yrs	not achieved

6.6.2 Effect of changing fuel price escalation rate

An increasing fuel escalation rate on the other hand, leads to increasing net savings from the Passive House retrofit measures. Net savings increase exponentially with increasing fuel inflation. The initial LCC calculation uses a fairly conservative 4% fuel inflation rate. Whilst there is much volatility and uncertainty in fuel prices, predicted escalation rates can be taken from historic data or energy outlook projections. The graph below shows the effect of varying the fuel escalation rate for the case study LCCA (Fig. 6.6) .

Although perhaps an unlikely long-term scenario, with static or falling fuel prices (≤ 2% inflation rate), the Passive House retrofit becomes no longer economic. Whilst at a fuel escalation rate of around 7% the Passive House retrofit overtakes the cheaper B3 'Shallow-Retrofit' alternative in terms of cost effectiveness. Assuming a future fuel inflation rate of 10% (unlikely perhaps but possible), the profits generated by the Passive House retrofit increase nearly eight-fold - to over €250,000.

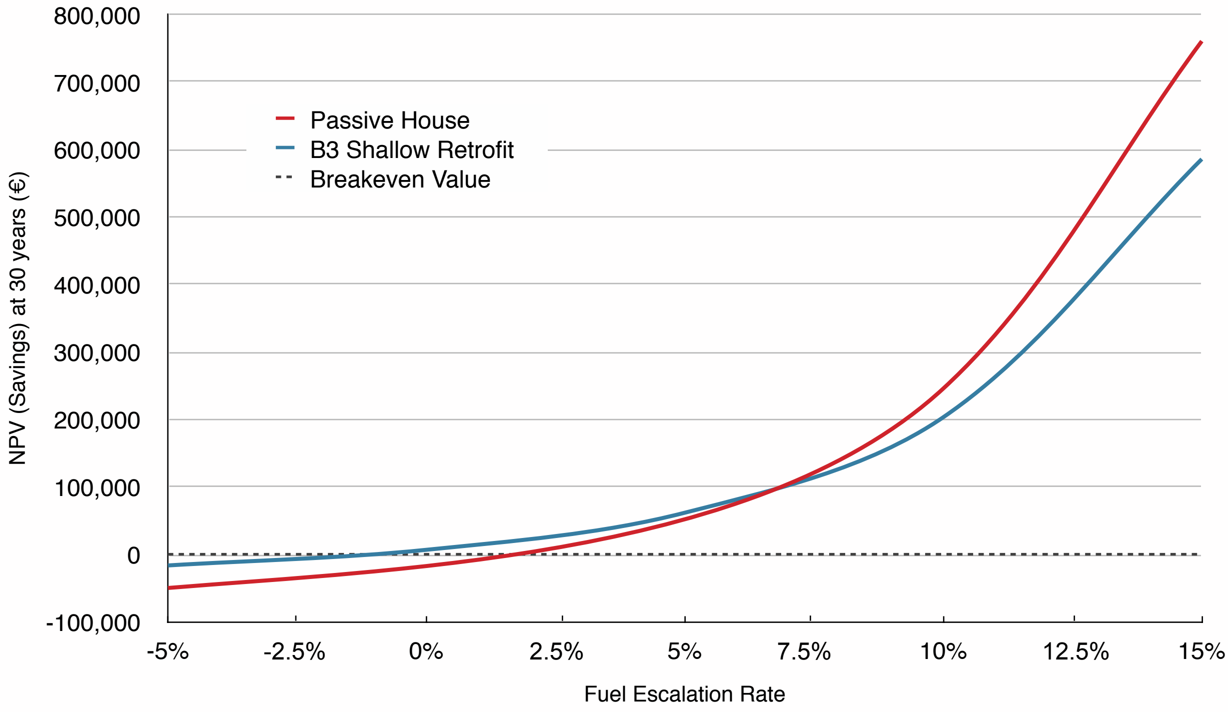


Fig. 6.6 Effect of fuel escalation rate on NPV (cost savings)

6.6.3 Effect of Changing Study Period

The longer the investment period considered, the greater the Net Savings generated by energy retrofitting. With a study period less than 19 years, the Passive House becomes no longer economic - operational energy savings accrued are not enough to offset the initial higher capital investment. Whilst with a study period of over 43 years the Passive House retrofit overtakes the cheaper B3 'Shallow-Retrofit' alternative. Assuming a 100 year investment period, the Net Savings (profits) generated by the investment in the Passive House retrofit increase to over €300,000 (Fig 6.7).

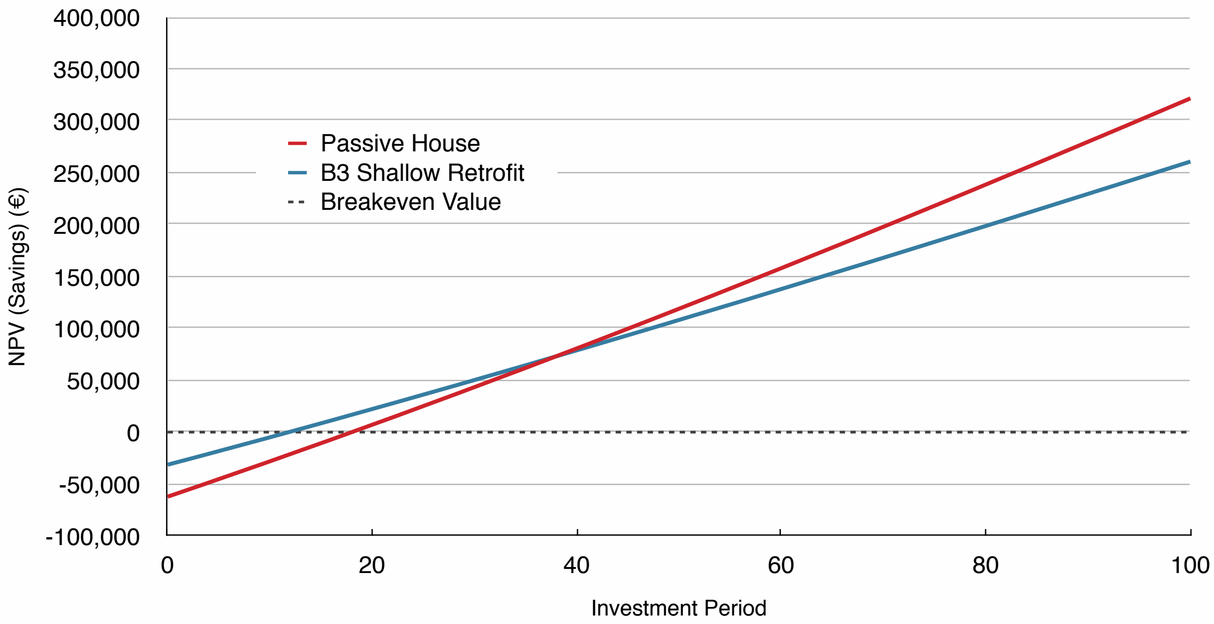


Fig. 6.7 Effect of length of study period on NPV (cost savings).

6.6.4 Effect of 'Performance Gap' on operational energy savings

Earlier it was discussed how there may be a significant differential between the predicted (i.e. as modelled in DEAP) and actual (measured) operational energy savings accrued by the Passive House retrofit measures. This 'performance gap' could arise for two different reasons:

- Performance gap between the predicted, or calculated energy efficiency of the retrofitted dwelling and the actual delivered energy performance in use (although for the Passive House case study dwelling it has been shown that the predicted and actual (monitored) energy usage for space heating and hot water are in fact very closely aligned).
- Overestimation of space heating energy use in the original pre-retrofitted dwelling as a result of occupancy behaviour or occupancy patterns (the house is simply not heated to required temperature and durations to meet assumed comfort conditions). Vesele *et al* (2009) for instance found a 60% difference between calculated and monitored space heating energy use in their case study pre-refurbishment dwelling (the pre-retrofit dwelling was using less than half the heat energy predicted in their energy modelling software).

To assess the LCC impact of such a potential discrepancy, the effect of reducing the calculated operational energy use of the base 'Do-nothing' dwelling has been assessed by LCCA (Table 6.4). The estimated space heating and domestic hot water demand for the base dwelling has been reduced by 10, 20, 30, 40 and 50%, and the NPV savings produced by the Passive House retrofit at Year 30 recalculated.

Table 6.4 Effect of reducing estimated operational energy in base dwelling on NPV savings

Initial LCCA Assumption	10% reduction	20% reduction	30% reduction	40% reduction	50% reduction
€34,626	€21,420	€8,209	-€4,988	-€18,195	-€31,402

If the operational energy demand for the base dwelling is assumed to be 30% lower than the amount predicted in the DEAP calculation, then the Passive House retrofit alternative now incurs a loss of €4,988 at the end of the 30 year investment period and so is no longer cost effective. With a 50% differential, losses on the investment increase to €31,402.

6.6.5 Capital investment cost variations

The LCC calculation is based on an input of initial capital investment costs required to carry out the Passive House retrofit works. In this study these were extracted from the architect's Final Account for total project costs, with the energy related costs isolated from general 'incidental' refurbishment costs. This differentiation of energy retrofit costs from incidental refurbishment costs is a matter of professional judgement, and in some case the distinction between costs is an artificial one - existing heating and ventilation systems, ground floor slabs, or windows may need total replacement for overriding functional or aesthetic reasons (incidental costs), regardless of any energy performance improvements, and subsequent energy cost savings delivered.

Furthermore, variables such as geographical location, market conditions, construction procurement methods and detailed specification requirements mean there can be uncertainty in assessing energy retrofit capital costs. Sensitivity analysis of initial construction costs has been included as part of the LCCA study. The initial LCCA calculation is based on an estimate of the capital cost of the energy retrofit works of €110,510. The initial costs estimate has been varied by a margin of +/- 10, 20, 30, & 40%, and the NPV Savings produced by the Passive House retrofit at Year 30 recalculated. If this capital costs estimate were to say increase above a value of approximately €155,000 (+40% cost variation), the Passive House retrofit then becomes un-economic.

Table 6.5 Effect of variations of initial capital costs (for energy retrofit works) on NPV savings

-20% variation	-10% variation	Initial Cost estimate	+10% variation	+20% variation	+30% variation	+40% variation
€51,791	€43,208	€34,626	€26,044	€17,462	€8,880	€298

6.6.6 Variations to residual values

In the initial LCCA calculations a residual value of 40% of the initial investment costs was assumed. This is based on an assumption of a continuing value beyond the 30 year study period (20 years remaining of 50 year life-span), and that the energy retrofit works in themselves give added value to the property, for which there is a market value.

Such a market residual value may in reality be difficult to quantify and is in the realm of speculation. If the LCCA is considered without the benefit of residual values (NPV of €24,689), the Passive House is still profitable, albeit with a much smaller profit margin and rate of return (NPV savings: €9,937, AIRR: 4.29%).

6.7 Summary of Chapter 5

The main conclusions from this results and analysis chapter are,

- The results of energy analysis indicate an estimated 95% reduction in total delivered energy and a 90% reduction in both CO_2 emissions and total energy costs achieved in the Passive House deep-retrofit over the original base-line (pre-retrofit) dwelling.

- The results of the LCCA study show that for the case study dwelling, assuming a 30 year investment term, 4% discount rate, and 4% fuel escalation rate, the Passive House retrofit is cost-effective, and even represents a profitable investment option for the private home-owner, particularly if capital residual values are included.
- On a purely financial basis however, the less expensive B3 'Shallow Retrofit' scenario is the more cost-optimal of all the alternatives considered, generating higher profits at the end of the 30 year term.
- Differing economic conditions can begin to favour the Passive House deep-retrofit over all other alternatives. Lower interest rates (< 2.7%), higher fuel escalation inflation rates (> 7%), or longer investment periods (> 43 years) all justify the greater initial capital investments in order to achieve higher long term operational savings over time.
- Conversely high interest rates (< 5.6%), static fuel prices (< 2%), or a short investment term (< 19 years) all render the Passive House retrofit uneconomic.

CHAPTER 7: Conclusions and Recommendations for Further Work

7.1 Conclusions of research

The primary aim of this study was to conduct an economic appraisal of the Passive House retrofit standard using Life Cycle Cost Analysis, in order to determine if it can become a cost-optimal standard for the deep-retrofit of Irish dwellings.

Following a review of relevant literature, a methodology was developed to investigate the problem. This involved energy analysis using DEAP, then compiling all relevant capital investment and operational cost data. This was followed by economic analysis using a freely available LCCA calculation tool (BLCC5 Program). The methodology was successfully tested and validated using a simple investment appraisal problem, consisting of a single energy retrofit measure (a replacement boiler). The LCCA methods, tools and assumptions are set out in a transparent way in order to be replicable both by other researchers, or by construction professionals carrying out similar economic analysis in the field.

A real life completed Irish Passive House retrofit project was then selected for analysis, and an individual approach developed for assessing the project's refurbishment capital costs, operational energy cost savings, and total life-cycle costs. Further comparative analysis was carried out for the baseline pre-retrofit dwelling and a range of alternative retrofit scenarios, including a 'systems upgrade only' approach, and a notional (BER) B3 rated 'shallow-retrofit'.

The case study project analysed in this study, demonstrates how a state-of-the-art, deep-retrofit of an existing dwelling can achieve advanced levels of energy performance. Energy analysis of the case study dwelling showed that reductions of over 90% in energy and CO_2 emissions can be delivered in a typical 'pre-regulations' Irish dwelling by deep retrofitting to the Passive House standard. Applied on a much wider scale, this offers the potential to realistically meet and even exceed the emissions reduction targets Ireland has committed itself to delivering by 2050.

Furthermore, a comparison between the (DEAP) calculated energy performance of the Passive House and monitored energy use over a 12 month period, indicates a good correlation between calculated, and actual energy performance in use. The Passive House dwelling is performing in accordance with the PHPP and DEAP predictive models. Measured energy use of the baseline (pre-retrofit) dwelling was not available meaning its actual energy usage could not be validated.

For the individual private homeowner, implementation of the Passive House retrofit standard offers the promise of vastly reduced fuel bills and even energy self-sufficiency. This is aside from the significant co-benefits of improved comfort and air-quality. The experience of living in a Passive House (as reported by the occupant of the case study dwelling) is generally that they are of superior comfort, maintain a consistent comfort temperature at all times and in all rooms, free of cold surfaces, draughts, and enjoy superior indoor air quality. However achieving the standard is clearly disruptive, costly, and for many unaffordable.

Yet the economic appraisal carried out in this study, using Life Cycle Cost Analysis suggests that the deep retrofitting of existing Irish dwellings to the Passive House standard can be cost effective for a private homeowner, with the right combination of interest rates (≤ 4%), fuel inflation (≥ 4%) long term investment periods (≥ 30 years), and the inclusion of residual values.

With these initial economic parameters, the LCCA calculation showed the Passive House was a cost effective, and even profitable investment option - generating a positive investment return over the 30 year investment time period. Although from a purely private, micro-economic perspective, a less intensive 'Shallow Retrofit' is likely to be more profitable, generating greater net savings over the assumed investment term.

However, with lower interest rates, longer investment timescales or higher fuel inflation, Passive House can become the cost-optimal standard. The study further demonstrated that increasing the life-span of the investment (> 43 Years), reducing interest rates (< 2.6%), or assuming a higher rate of fuel price escalation (> 7%), all increase the cost effectiveness of the Passive House and justify (economically) the higher capital investment.

The results of this LCCA study appears to agree generally with the conclusions reached by Neroutsou (2014), and Versele *et al* (2009). Most importantly, like these earlier studies, in a similar way the effect of changing the key economic variables was noted. The sensitivity analysis carried out as part of the study was vital in highlighting the impact on any cost-benefit financial assessment when the economic parameters are altered. The question becomes less then about 'is the Passive House retrofit standard cost-optimal?' and more, 'what economic conditions and investment parameters do we need in place to make it cost-optimal?'

7.2 Recommendations for further research

This research focused on an economic assessment of a specific case study Passive House retrofit. Although more general conclusions can be drawn from the research findings, the limitations of a study based on an individual case study need to be recognised. The original (pre-retrofit) dwelling selected, had its own unique construction characteristics, performance defects and associated costs, particular to the building's original state as well as the owners specific brief for the incidental (non-energy-related) works. However, the approach taken by this research could be applied to other case study buildings, in order to draw wider conclusion as to the cost-effectiveness of Passive House. The methodology used in this study has been carefully explained in Chapter 3, and demonstrated in Chapter 4, allowing others to perform similar calculations for different house types, geographic locations, energy standards and other conditions.

The study was also limited in scope to an analysis of life-cycle costs from the private perspective of an individual home-owner, assumed to be financing the retrofit works through a commercial loan. An economic analysis from a wider societal perspective also needs to be considered. This would involve expanding the life-cycle cost assessment to include the additional environmental benefits of reduced carbon emission abatement costs. What are the true life cycle costs of CO_2 emissions if they were to be transferred onto individual private homeowners through carbon taxes or fuel taxes?

The research also highlighted how there could be potential performance-gap between (DEAP modelled) predicted energy use and actual post-occupancy energy use, particularly in existing dwellings with poor energy performance characteristics. Such a discrepancy could lead to an overestimation of the energy and emissions savings achieved in reality, both on a national state level, as well as for individual householders. There needs to be significant research and occupancy monitoring within existing dwellings (both pre- and post-retrofit), to identify whether the predicted operational energy cost savings are being achieved in reality.

Finally, like the studies carried out by Brophy *et al* (2009), Famuyibo (2012), and Ahern *et al* (2013), the methodology used in this research for the assessment of the life cycle costs of a single dwelling could be applied on a much wider scale to assess the entire Irish housing stock, or specific elements of it. It would be expected that significant discounts on retrofit costs could be available with a mass take-up of deep-retrofit. Bulk-financing could be anticipated through central and european bank loans with lower interest rates and longer investment terms. In such a scenario, what would it cost to retrofit Ireland’s 2 million homes to Passive House standard? Could this become cost-optimal?

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GLOSSARY:

(Definitions given in this glossary are specific to the context of the dissertation).

Air-tightness layer Membrane or structural layer which resists air infiltration through the structure. Essential for reducing heat losses occurring though air leakage. May be sometimes combined with function of a Vapour Barrier, whose purpose is to prevent moisture from inside the building permeating into the structure, with potential for interstitial condensation, mould growth and structural damage.

Background ventilation Openings or vents located in external walls or windows to enable continuous natural ventilation in a dwelling. Background vents may have an adjustable setting to allow some user control ('Hit & Miss' vents). Any room with an open gas appliance or solid fuel fire will additionally require permanent ventilators which cannot be closed.

Capital costs Initial 'up-front' costs required to retrofit or implement energy efficient measures. Includes both procurement, installation and relevant ancillary costs.

Cavity wall Double skin wall construction with two block or brickwork layers separated by a cavity. The cavity may either be a clear air-space, filled with insulation or party filled. Un-filled cavity walls can be retrofitted with blown polystyrene insulation injected into the cavity under pressure.

Condensing boiler Gas or oil-fired heating boiler with ability to utilise heat from from flue gasses that would otherwise be lost to the outside air, thus increasing efficiency. Efficiencies of up to 92% are possible in modern condensing boilers, as opposed to typical efficiency of 75-80% in a non-condensing boiler.

Dwelling Energy Assessment Procedure (DEAP) Energy analysis tool and calculation software. The official Irish methodology for calculation and rating the energy performance of dwellings. Available as a Windows software program or cross-platform Excel Workbook.

Delivered energy Energy consumption within a dwelling required for heating, cooling, hot water, lighting and auxiliary electrical. Corresponds with the actual measured energy use appearing on fuel utility bills. Measured in kilowatt hours per metre squared of floor area per year ($kWh/m^2/yr$).

Discounting Mathematical technique to convert all costs and benefits arising at a future date into a present unit of currency (i.e. in 'today's money')

Energy retrofitting Refurbishment and installation of new components, fabric upgrades or new systems into existing buildings, in order to increase energy efficiency and thermal comfort. 'Deep Retrofit' generally involves significant fabric upgrades (wall, floor and roof insulation), energy efficient replacement windows (double or triple glazing), air-tightness measures, and updating heating, hot water and ventilation systems.

EnerPHit Version of the Passive House Standard developed for the retrofit of existing buildings. Buildings that have been retrofitted with Passive House components and to the required energy performance criteria, can achieve the slightly lesser EnerPHit certification as evidence of both building quality and fulfilment of specific energy values. EnerPHit standard allows for a marginally relaxed air-tightness standard (1.0 ach) and maximum specific space heating demand (25 kWh/m^2/yr).

External wall insulation (EWI) Rigid insulation applied to outside envelope of structure to increase its thermal performance. Normally installed as part of a system incorporating an external render outer finish layer. Generally seen as preferable in retrofit works as the insulation layer can be applied uninterrupted over all surfaces and junctions, minimising thermal bridges and reducing risk of interstitial condensation.

Heat load Maximum heat required on the coldest day of the year. Measured in watts (W) per metre squared (m^2) of floor area.

Heat pump Device that makes use of the ambient heat from the environment, either from the ground, air or water. Latent heat from the environment is extracted and amplified via a compressor. Generally operate from electricity but can have efficiencies of over 400% (meaning 4 kWh of heat can be generated from 1 kWh of electricity).

Investment appraisal An economic evaluation of the attractiveness of an investment proposal or project alternative, using methods such as adjusted internal rate of return (AIRR), net present value (NPV) or payback period. Normally would include an assessment of the future costs and benefits over the project's life. An investment appraisal is an integral part of any capital budgeting or financial decision making.

Mechanical ventilation with heat recovery (MVHR) Mechanical ventilation system incorporating a fan unit and heat exchanger to recover heat from the extracted stale air that would otherwise be lost to outside. The heat is extracted by the heat exchanger and used to heat incoming cool fresh air. To be efficient the system requires a well sealed and airtight structure.

Mineral wool Insulation material made from molten glass, inorganic rock or slag (e.g. 'Rockwool'). Available as flexible rolls for insulation of roof or attic spaces, or as rigid batts for external wall insulation.

Nearly Zero Energy Building (nZEB) Building with an ultra low energy demand for heating, cooling, ventilation, light and power, and with this residual energy demand being met mainly by on site or nearby renewable energy sources. For dwellings, equivalent to an A2 BER rating (Primary Energy Demand ≤ 45 kWh/m^2/yr). From 2020 onwards, all new buildings in Ireland must be constructed as nZEBs.

n50 Passive House air-tightness measurement **-** total air changes per hour at 50 Pascals pressurisation / depressurisation. Units are air changes per hour (ach @50Pa). It must be an average of the pressurisation and depressurisation tests.

Payback Period Number of years before a particular measure or retrofit alternative will have paid for itself (i.e. the benefits will have equalised the costs).

Passive House Planning Package (PHPP) Passive House energy analysis tool and calculation software. The key design tool for the planning of Passive House buildings and verification of the Passive House standard. Like DEAP, its format is a series of interlinked Excel spreadsheets in one workbook. Although based on simplified calculations, PHPP has been calibrated from from complex dynamic simulation models.

Photovoltaics Generation of electricity by conversion of solar radiation into direct current (DC) electricity using photovoltaic panels. The system must include an inverter to convert DC electricity to AC before being fed into the main fuse board of the dwelling.

Primary energy Primary Energy includes not only delivered energy but also the losses from distribution, conversion and delivery to the end-user. For electricity, for example, the generation efficiency of power stations as well as electricity transmission and distribution losses are included. DEAP and PHPP incorporate primary energy factors for each fuel type to convert Deliver Energy to Primary Energy. Measured in kilowatt hours per metre squared of floor area per year ($kWh/m^2/yr$).

q50 Air-tightness measurement used in DEAP - total air changes per hour at 50 Pascals pressurisation / depressurisation. This measurement is the m^3 of air passing through each m^2 of the building fabric per hour at 50 Pascals (@50Pa). It is measured in ($m^3/h/m^2$ @50Pa).

Sensitivity Analysis Study of uncertainty and risk within a mathematical model or system. In LCCA there are always variables that are uncertain or unpredictable - e.g. interest rates, fuel inflation, time-scale, future replacement costs. Sensitivity analysis is used to test the robustness of the the results in the presence of uncertainty. Can be used to examine the effect on the calculations of changing variables, and also examine which of the variables will have the most significant impact.

Secondary space heating system Space heating systems supplementing the primary heating system. Typically in older dwellings this may be a solid-fuel burning open fire or stove.

Solar water heating System of generating thermal energy from solar collectors (solar panels), usually mounted on roof of dwelling, preferably facing south at a 30º angle. Generally will contribute up to 50% of energy required for domestic hot water

Space heating demand The total energy required to heat the building for a year. Measured in kilowatt-hours (kWh) per metre squared (m^2) of floor area per year (a).

Thermal bridge A localised weak area in the envelope of a building where heat flow is increased compared to adjacent areas. Thermal bridges can often become apparent at the junctions of two or more elements (e.g. wall-floor junction). The main effects associated with thermal bridges are increased heat loss as well as a localised reduction in internal surface temperature which can in turn lead to increased risk of surface condensation and mould growth. Passive house retrofits are generally designed to be thermal bridge free is so far as is practical. Thermal bridge is measured by the heat flow through the bridge represented by its Ψ-value (psi value) in watts per metre Kelvin W/mK.

Thermal conductivity The capacity of a material to conduct heat. Measured in watts per metre Kelvin (W/(mK). The lower the thermal conductivity value the better the thermal insulation qualities of a material.

U-value Measure of rate of heat transfer through a building element (i.e. wall or window). Measured in Watts per metre squared per degree Kelvin (W/m^2K). A wall with a U-Value of 1.0 W/m^2K will allow 1 Watt pass through it when there is a temperature difference of 1 degree between the inside and outside. Well insulated elements will have low U-Values (e.g 0.15 W/m^2K), whereas poorly-insulated elements will have high U-Values (e.g 5.0 W/m^2K)

APPENDICES:

Appendix A DEAP Calculations Results - LCCA Validation exercise (boiler replacement).

Appendix B Excel spreadsheet - LCCA Validation exercise (boiler replacement).

Appendix C BLCC5 Cost Analysis Report - LCCA Validation exercise (boiler replacement).

Appendix D DEAP Calculations Results - Case study dwelling.

Appendix E Project cost breakdown - Case study dwelling - Passive House Retrofit.

Appendix F Project cost breakdown - Case study dwelling - B3 'Shallow Retrofit'.

Appendix G BLCC5 Cost Analysis Report - Case study dwelling - Passive House Retrofit.

Appendix H BLCC5 Cost Analysis Report - Case study dwelling - B3 'Shallow Retrofit'.

Appendix A DEAP Calculations Results - LCCA Validation exercise (boiler replacement)

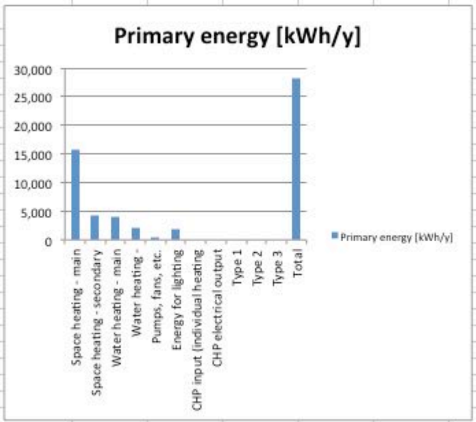
DEAP Results - Existing Boiler

Results

	Delivered energy [kWh/y]	Primary energy [kWh/y]	CO_2 emissions [kg/y]
Space heating - main	14,263	15,689	2,895
Space heating - secondary	3,783	4,161	1,396
Water heating - main	3,580	3,938	727
Water heating - supplementary	911	2,204	477
Pumps, fans, etc.	169	409	89
Energy for lighting	781	1,890	409
CHP input (individual heating systems only)	0	0	0
CHP electrical output (individual heating system	0	0	0
Type 1 -	0	0	0
Type 2 -	0	0	0
Type 3 -	0	0	0
Total	23,486	28,291	5,993
per m^2 floor area	241.6	291.03	61.65
		[kWh/m^2 y]	
Building Energy Rating		291	D2

Check conformity with MPEPC and MPCPC requirements in TGD L
Relevant for new-build.

	Primary energy [kWh/y]	CO2 emissions [kg/y]
Totals for reference dwelling	14,218	2,952
	EPC	CPC
Performance coefficients	1.990	2.030
Maximum permitted	0.400	0.460
	Does not comply	Does not comply



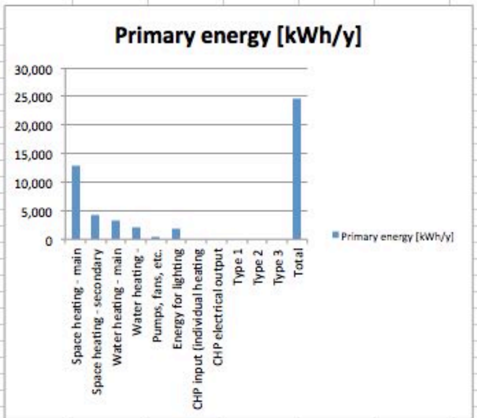
DEAP Results - Replacement Boiler

Results

	Delivered energy [kWh/y]	Primary energy [kWh/y]	CO_2 emissions [kg/y]
Space heating - main	11,628	12,790	2,360
Space heating - secondary	3,783	4,161	1,396
Water heating - main	2,918	3,210	592
Water heating - supplementary	911	2,204	477
Pumps, fans, etc.	169	409	89
Energy for lighting	781	1,890	409
CHP input (individual heating systems only)	0	0	0
CHP electrical output (individual heating system	0	0	0
Type 1 -	0	0	0
Type 2 -	0	0	0
Type 3 -	0	0	0
Total	20,189	24,664	5,324
per m^2 floor area	207.7	253.72	54.76
		[kWh/m^2 y]	
Building Energy Rating		254	D1

Check conformity with MPEPC and MPCPC requirements in TGD L
Relevant for new-build.

	Primary energy [kWh/y]	CO2 emissions [kg/y]
Totals for reference dwelling	14,218	2,952
	EPC	CPC
Performance coefficients	1.735	1.804
Maximum permitted	0.400	0.460
	Does not comply	Does not comply



Appendix B Excel spreadsheet - LCCA Validation exercise (boiler replacement)

SIMPLE LCCA CALCULATION SHEET **Example: Comparative Life Cycle Costs for Existing Boiler (75% efficient) & Replacement Condensing Boiler (92% efficient)**

Inputs & PV Formulae:

Length of Study (years)	20	Fuel Use (Existing Boiler)	17500
Life of Component	20	Fuel Use (New Boiler)	14200
Discount Rate (as decimal)	0.03	Fuel Costs € per kWh	0.0681
Fuel Escalation Rate (as decimal)	0.04	SPV* (residual)	1.213171759
Escalation Rate (Inflation)	0.02	SPV* (replacement)	1.213171759
Residual Value Option A	0	UPV* 1 (Repair Costs)	18.08122939
Residual Value Option B	0	UPV* 2 (Fuel Costs)	22.16986291

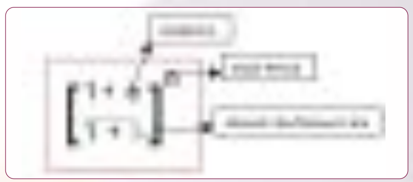
Life Cycle Cost Calculation:	Initial Costs +	(Replacement Cost	x SPV replacement) +	(Annual Repair Cost	x UPV 1) +	(Annual Energy Costs	x UPV 2) -	Residual Value	Total LCC (NPV)	
OPTION A (KEEP EXISTING BOILER)	0	0	1.213171759	100	18.08122939	1191.75	22.16986291	0	€ 28,229.06	OPTION A LCC
OPTION B (REPLACE BOILER)	2000	0	1.213171759	100	18.08122939	967.02	22.16986291	0	€ 25,246.82	OPTION B LCC
									€ 2,982.23	NET SAVINGS

Present Value Formulae in Excel (From SCSI Guide to Life Cycle Costing 2013):

3.4 Single Present Value Modified (SPV*)

The SPV* factor is similar to the SPV calculation outlined previously, except SPV* allows for the incorporation of escalation (e) into the calculation. This factor is used when the cost today is known (or estimated) and a relevant escalation rate is applied over a certain period of time to estimate the future cost of the building component. The formulae allows for the escalation and discounting factors to be incorporated in the same calculation.

$$SPV^* = \left[\frac{1+e}{1+i}\right]^n$$



The SPV* formula shown above could be written into an excel cell as follows;

3.5 Uniform Present Value Modified (UPV*)

The UPV* calculation is similar to the UPV calculation outlined previously. The original amount is escalated on a yearly basis and is discounted proportionally throughout the building life cycle. An example of this is energy costs which can be reasonably estimated in today's costs. Applying an escalation rate (e) to energy costs on a yearly basis over the life cycle and discounting (i) the costs will provide you with a cumulative PV cost.

$$UPV^* = \frac{1 - \left[\frac{1+e}{1+i}\right]^n}{\left[\frac{1+i}{1+e}\right] - 1}$$

The UPV* formula above could be written into an excel cell as follows;

Appendix C BLCC5 Cost Analysis Report - LCCA Validation exercise (boiler replacement)

NIST BLCC 5.3-13: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing Boiler retained (75% efficient)

Alternative: New Boiler

General Information

File Name:	/Applications/BLCC5/projects/Simple Test 1 - new boiler.xml
Date of Study:	Thu Apr 30 20:39:15 IST 2015
Project Name:	Jamestown Aveneu New Boiler
Project Location:	U.S. Average
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	D Coyle
Comment	Simple LCC calculation - should I replace my gas Boiler with more efficient condensing boiler
Base Date:	April 1, 2013
Service Date:	April 1, 2013
Study Period:	20 years 0 months(April 1, 2013 through March 31, 2033)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$2,000	-$2,000
Future Costs:			
Energy Consumption Costs	$26,420	$21,438	$4,982
Energy Demand Charges	$0	$0	$0
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$1,808	$1,808	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	$0	$0
Subtotal (for Future Cost Items)	$28,228	$23,246	$4,982
Total PV Life-Cycle Cost	$28,228	$25,246	$2,982

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$4,982
- Increased Total Investment	$2,000
Net Savings	$2,982

Savings-to-Investment Ratio (SIR)

SIR = 2.49

Adjusted Internal Rate of Return

AIRR = 7.81%

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Simple Payback occurs in year 8

Discounted Payback occurs in year 9

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Natural Gas	17,500.0 kWh	14,200.0 kWh	3,300.0 kWh	65,991.0 kWh

Appendix D DEAP Calculations Results - Case study dwelling

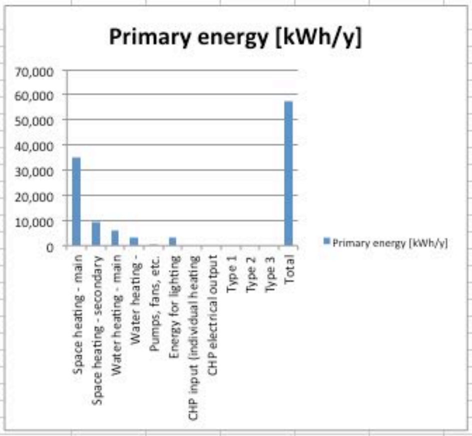
DEAP Results - Baseline (Existing) dwelling

Results

	Delivered energy [kWh/y]	Primary energy [kWh/y]	CO_2 emissions [kg/y]
Space heating - main	31,768	34,945	8,641
Space heating - secondary	8,420	9,262	3,039
Water heating - main	5,354	5,889	1,456
Water heating - supplementary	1,471	3,486	768
Pumps, fans, etc.	230	545	120
Energy for lighting	1,326	3,143	692
CHP input (individual heating systems only)	0	0	0
CHP electrical output (individual heating systen	0	0	0
Type 1 -	0	0	0
Type 2 -	0	0	0
Type 3 -	0	0	0
Total	48,568	57,269	14,717
per m^2 floor area	327.0	385.60	99.09
		[kWh/m² y]	
Building Energy Rating		386	F

Check conformity with MPEPC and MPCPC requirements in TGD L
Relevant for new-build.

	Primary energy [kWh/y]	CO2 emissions [kg/y]
Totals for reference dwelling	21,176	4,445
	EPC	CPC
Performance coefficients	2.704	3.311
Maximum permitted	0.400	0.460
	Does not comply	Does not comply



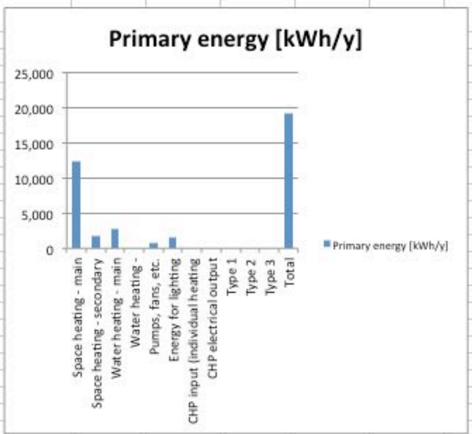
DEAP Results - B3 - 'Shallow Retrofit'

Results

	Delivered energy [kWh/y]	Primary energy [kWh/y]	CO_2 emissions [kg/y]
Space heating - main	11,170	12,287	3,038
Space heating - secondary	1,622	1,784	598
Water heating - main	2,450	2,695	666
Water heating - supplementary	0	0	0
Pumps, fans, etc.	335	794	175
Energy for lighting	634	1,503	331
CHP input (individual heating systems only)	0	0	0
CHP electrical output (individual heating systen	0	0	0
Type 1 PV	0	0	0
Type 2 -	0	0	0
Type 3 -	0	0	0
Total	16,211	19,064	4,809
per m^2 floor area	115.5	135.88	34.28
		[kWh/m² y]	
Building Energy Rating		136	B3

Check conformity with MPEPC and MPCPC requirements in TGD L
Relevant for new-build.

	Primary energy [kWh/y]	CO2 emissions [kg/y]
Totals for reference dwelling	20,275	4,254
	EPC	CPC
Performance coefficients	0.940	1.131
Maximum permitted	0.400	0.460
	Does not comply	Does not comply



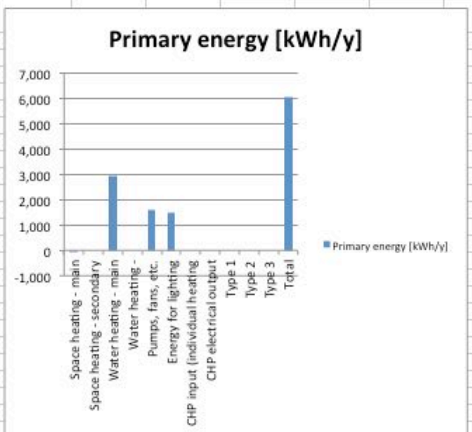
DEAP Results - Passive House Retrofit

Results

	Delivered energy [kWh/y]	Primary energy [kWh/y]	CO_2 emissions [kg/y]
Space heating - main	-1	-1	0
Space heating - secondary	0	0	0
Water heating - main	1,243	2,947	649
Water heating - supplementary	0	0	0
Pumps, fans, etc.	665	1,575	347
Energy for lighting	634	1,503	331
CHP input (individual heating systems only)	0	0	0
CHP electrical output (individual heating systen	0	0	0
Type 1 -	0	0	0
Type 2 -	0	0	0
Type 3 -	0	0	0
Total	2,542	6,024	1,327
per m^2 floor area	18.1	42.93	9.46
		[kWh/m² y]	
Building Energy Rating		43	A2

Check conformity with MPEPC and MPCPC requirements in TGD L
Relevant for new-build.

	Primary energy [kWh/y]	CO2 emissions [kg/y]
Totals for reference dwelling	20,255	4,249
	EPC	CPC
Performance coefficients	0.297	0.312
Maximum permitted	0.400	0.460
	Complies	Complies



Appendix E Project cost breakdown - Case study dwelling - Passive House Retrofit

Item	Total Costs	PH Costs	%	Non PH Costs	%	Notes
Preliminaries.	3,016.00	2,050.88	68%	965.12	32%	Costs allocated on Pro-rata basis between PH / Non PH
Scaffolding	3,016.00	3,016.00	100%	-00	0%	Scafolding reqd. primarily for EWI & Roof alterations / Insulation
External Demolitions and Disposal	4,919.20	1,967.68	40%	2,951.52	60%	PH: Removal windows & sills, rw goods, perimeter trench, chimney
Internal Demolitions and Disposal	10,717.20	5,358.60	50%	5,358.60	50%	PH: break up and remove floor slab, remove ceilings, partition ends
Structural Beams.	1,083.68	-00	0%	1,083.68	100%	Required for layout changes, not related to PH measures
Ground Floor Slab	8,499.25	7,649.33	90%	849.93	10%	Structural Condition of existing floor slab? Dampness?
Radon barrier and sump	3,026.40	-00	0%	3,026.40	100%	Consequential Regs requirement arising out of floor replacement ?
New Blockwork.	1,822.08	728.83	40%	1,093.25	60%	PH: altering window opes to north elevations - reduce heat loss?
1st Fix Carpentry	6,916.00	3,458.00	50%	3,458.00	50%	PH: altering or replacing internal stud walls to achive airtightness
Airtight - Seal round windows	865.28	865.28	100%	-00	0%	
Airtight - Mastic	260.00	260.00	100%	-00	0%	
Airtight Layer - First floor Ceiling	1,430.00	1,430.00	100%	-00	0%	
Airtight - Testing	546.00	546.00	100%	-00	0%	
Acoustic Dry lining to parting wall	936.00	-00	0%	936.00	100%	Acoustic measure
Pumped insulation to Cavity Walls	939.64	939.64	100%	-00	0%	
Insulation - External wall Insulation	20,367.80	19,349.41	95%	1,018.39	5%	Some EWI costs attributed to new build - porch addition
Insulation – Ceiling/boxing Insulation	3,369.60	3,369.60	100%	-00	0%	
Insulation - To Eaves	1,196.00	1,196.00	100%	-00	0%	
Allowance for the Electrical Installation.	3,500.00	350.00	10%	3,150.00	90%	PH: wiring of Heat Pump & MVHR, Low energy light fittings?
New Windows and Doors	7,300.00	7,300.00	100%	-00	0%	Assumes existing original windows & doors were servicable
Plus 5% on windows PC Sum	365.00	365.00	100%	-00	0%	
Powder coated window cills.	910.00	910.00	100%	-00	0%	
Allowance for Heating System	13,809.60	11,047.68	80%	2,761.92	20%	Was existing heating system servicable? E/O costs for heat pump
Allowance for the supply and fit of the HRV System	5,781.30	5,203.17	90%	578.13	10%	Bathroom / kitchen extracts in original house? E/O costs
General Plumbing.	1,664.00	-00	0%	1,664.00	100%	Assumes re-plumb was required regardless of PH measures
Thermal bridge elimination	1,508.00	1,508.00	100%	-00	0%	What works are covered under this element?
Internal Plastering & patching.	5,304.00	3,978.00	75%	1,326.00	25%	PH: repairs / patching to internal plaster to achieve airtight layer
Joinery – Internal Joinery Allowance	1,851.20	1,110.72	60%	740.48	40%	PH: new skirting etc. required after plastering at joist ends etc.
Joinery - Allowance for extra Ironmongery	150.00	-00	0%	150.00	100%	Non PH cost
Joinery - New staircase	1,716.00	-00	0%	1,716.00	100%	Non PH cost
Allowance for the supply of Sanitary Ware.	1,800.00	-00	0%	1,800.00	100%	Non PH cost - replacement interal fittings
Insulated Cover to Attic Access Hatch	285.00	285.00	100%	-00	0%	
Attic - Attic Access Floor	728.00	-00	0%	728.00	100%	Non PH cost
Roof – Tile and Barge Extension.	3,224.00	3,224.00	100%	-00	0%	Required due to EWI, chimney removal. Total Re-roof optional?
Flat roof	520.00	-00	0%	520.00	100%	Non PH cost - new build - porch addition
Rainwater Goods	2,751.84	1,651.10	60%	1,100.74	40%	Required due to EWI & altered eaves - replacement optional?
External Works and finishes	5,200.00	1,040.00	20%	4,160.00	80%	Making good conc. screeds around foundation trenches (EWI)
ADDITIONAL WORKS						
18mm Ply to Ground Floor	1,627.60	-00	0%	1,627.60	100%	Assumes existing floor finishes needed replacement
150mm fibreglass to intermediate floor	376.74	-00	0%	376.74	100%	Acoustic measure
Extra concrete to rear path	350.00	-00	0%	350.00	100%	Non PH cost?
Construction Costs Sub Total	132,921.67	90,157.92		42,763.75		
Add for VAT @ 13.5%	17,944.43	12,171.32		5,773.11		Portion of VAT reclaimable through HRI scheme (see below)
Total Construction Costs Including vat @ 13.5%	150,866.10	102,329.24	68%	48,536.86	32%	
ANCILLARY & INDIRECT COSTS						
Painting & Decoration (Incl. VAT)	2,500.00	-00	0%	2,500.00	100%	
Fitted Kitchen & Appliances (Incl. VAT)	3,000.00	-00	0%	3,000.00	100%	
Other Fittings/ Items purchased by Client directly	500.00	-00	0%	500.00	100%	
Professional Fees - Architect, Engineer etc. (Incl. VAT)	14,514.00	9,869.52	68%	4,644.48	32%	Allocated on Pro rata basis.
Planning Application Costs & Charges	500.00	340.00	68%	160.00	32%	Allocated on Pro rata basis between PH / Non PH
Passive House Certification	1,500.00	1,500.00	100%	-00	0%	Cost of Quality Assurance - shows PH standard has been reached
SEAI Grants - rebate	- 2,950.00	- 2,950.00	100%	-00	0%	
HRI Scheme VAT rebate	- 4,050.00	- 2,754.00	68%	- 1,296.00	32%	Assumes Contractor / Client eligible to claim back VAT
Temp. Relocation Costs (4 Months Rent - €800 pm?)	3,200.00	2,176.00	68%	1,024.00	32%	10 month construction period? May 2013- March 2014?
TOTAL INITIAL CAPITAL COSTS	€ 169,580.10	€ 110,510.76	65%	€ 59,069.34	35%	
ESTIMATED CAPITAL COSTS OF PASSIVE HOUSE RETROFIT		€ 110,510.76				
COSTS PER m2 (142m2)	€ 1,194.23	€ 778.24		€ 415.98		

Appendix F Project cost breakdown - Case study dwelling - B3 'Shallow Retrofit

Item	Total Costs	B3 Retrofit Costs	%	Incidental Costs	%	Notes
Preliminaries.	2,171.12	1,206.00	40%	965.12	60%	Costs allocated on Pro-rata basis between PH / Non PH
Scaffolding	3,016.00	3,016.00	100%	-00	0%	Scafolding reqd. primarily for EWI & Roof alterations / Insulation
External Demolitions and Disposal	3,442.00	491.00	10%	2,951.00	90%	PH: Removal windows & sills, rw goods, perimeter trench, chimney
Internal Demolitions and Disposal	5,893.00	535.00	5%	5,358.00	95%	PH: break up and remove floor slab, remove ceilings, partition ends
Structural Beams.	1,083.00	-00	0%	1,083.00	100%	Required for layout changes, not related to PH measures
Ground Floor Slab	849.00	-00	0%	849.00	100%	Structural Condition of existing floor slab? Dampness?
Radon barrier and sump	3,026.00	-00	0%	3,026.00	100%	Consequential Regs requirement arising out of floor replacement ?
New Blockwork.	1,275.00	182.00	10%	1,093.00	90%	PH: altering window opes to north elevations - reduce heat loss?
1st Fix Carpentry	3,458.00	-00	0%	3,458.00	100%	PH: altering or replacing internal stud walls to achive airtightness
Airtight - Seal round windows	-00	-00	0%	-00	100%	
Airtight - Mastic	-00	-00	0%	-00	100%	
Airtight Layer - First floor Ceiling	-00	-00	0%	-00	100%	
Airtight - Testing	-00	-00	0%	-00	100%	
Acoustic Dry lining to parting wall	936.00	-00	0%	936.00	100%	Acoustic measure
Pumped insulation to Cavity Walls	939.00	939.00	100%	-00	0%	
Insulation - External wall Insulation	17,312.00	16,294.00	80%	1,018.00	20%	Some EWI costs attributed to new build - porch addition
Insulation – Ceiling/boxing Insulation	2,358.00	2,358.00	70%	-00	30%	
Insulation - To Eaves	598.00	598.00	50%	-00	50%	
Allowance for the Electrical Installation.	3,500.00	175.00	5%	3,325.00	95%	PH: wiring of Heat Pump & MVHR, Low energy light fittings?
New Windows and Doors	5,840.00	5,840.00	80%	-00	20%	Assumes existing original windows & doors were servicable
Plus 5% on windows PC Sum	292.00	292.00	80%	-00	20%	
Powder coated window cills.	910.00	910.00	100%	-00	0%	
Allowance for Heating System	9,665.00	6,904.00	50%	2,761.00	50%	Was existing heating system servicable? E/O costs for heat pump
Allowance for the supply and fit of the HRV System	1,156.00	578.00	10%	578.00	90%	Bathroom / kitchen extracts in original house? E/O costs
General Plumbing.	1,664.00	-00	0%	1,664.00	100%	Assumes re-plumb was required regardless of PH measures
Solar HW Panel	4,500.00	4,500.00	100%	-00	0%	
Thermal bridge elimination	-00	-00	0%	-00	100%	What works are covered under this element?
Internal Plastering & patching.	1,326.00	-00	0%	1,326.00	100%	PH: repairs / patching to internal plaster to achieve airtight layer
Joinery – Internal Joinery Allowance	740.00	-00	0%	740.00	100%	PH: new skirting etc. required after plastering at joist ends etc.
Joinery - Allowance for extra Ironmongery	150.00	-00	0%	150.00	100%	Non PH cost
Joinery - New staircase	1,716.00	-00	0%	1,716.00	100%	Non PH cost
Allowance for the supply of Sanitary Ware.	1,800.00	-00	0%	1,800.00	100%	Non PH cost - replacement interal fittings
Insulated Cover to Attic Access Hatch	-00	-00	0%	-00	100%	
Attic - Attic Access Floor	728.00	-00	0%	728.00	100%	Non PH cost
Roof – Tile and Barge Extension.	1,535.00	1,534.00	20%	1.00	80%	Required due to EWI, chimney removal. Total Re-roof optional?
Flat roof	520.00	-00	0%	520.00	100%	Non PH cost - new build - porch addition
Rainwater Goods	2,751.00	1,651.00	60%	1,100.00	40%	Required due to EWI & altered eaves - replacement optional?
External Works and finishes	5,200.00	1,040.00	20%	4,160.00	80%	Making good conc. screeds around foundation trenches (EWI)
<u>ADDITIONAL WORKS</u>						
18mm Ply to Ground Floor	1,627.00	-00	0%	1,627.00	100%	Assumes existing floor finishes needed replacement
150mm fibreglass to intermediate floor	376.00	-00	0%	376.00	100%	Acoustic measure
Extra concrete to rear path	350.00	-00	0%	350.00	100%	Non PH cost?
Construction Costs Sub Total	92,702.12	49,043.00		42,694.00		
Add for VAT @ 13.5%	12,514.79	6,620.81		5,763.69		Portion of VAT reclaimable through HRI scheme (see below)
Total Construction Costs Including vat @ 13.5%	105,216.91	55,663.81	53%	48,457.69	47%	
<u>ANCILLARY & INDIRECT COSTS</u>						
Painting & Decoration (Incl. VAT)	2,500.00	-00	0%	2,500.00	100%	
Fitted Kitchen & Appliances (Incl. VAT)	3,000.00	-00	0%	3,000.00	100%	
Other Fittings/ Items purchased by Client directly	500.00	-00	0%	500.00	100%	
Professional Fees - Architect, Engineer etc. (Incl. VAT)	11,945.00	5,972.50	50%	3,500.00	50%	Allocated on Pro rata basis.
Planning Application Costs & Charges	500.00	300.00	60%	200.00	40%	Allocated on Pro rata basis between PH / Non PH
Passive House Certification	-00	-00	0%	-00	100%	Cost of Quality Assurance - shows PH standard has been reached
SEAI Grants - rebate	- 2,950.00	- 2,950.00	100%	-00	0%	
HRI Scheme VAT rebate	- 4,050.00	- 2,025.00	50%	- 2,025.00	50%	Assumes Contractor / Client eligible to claim back VAT
Temp. Relocation Costs (2 months Rent - €800 pm?)	1,600.00	480.00	30%	1,120.00	70%	10 month construction period? May 2013- March 2014?
TOTAL INITIAL CAPITAL COSTS	€ 118,261.91	€ 57,441.31	49%	€ 57,252.69	51%	
ESTIMATED CAPITAL COSTS OF B3 SHALLOW RETROFIT		€ 57,441.31				
COSTS PER m2 (142m2)	€ 832.83	€ 404.52		€ 403.19		

NIST BLCC 5.3-13: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Base Case - "Do Nothing"

Alternative: EnerPHit Retrofit

General Information

File Name:	/Applications/BLCC5/projects/Galway PH LCCA/Galway PH LCC Final.xml
Date of Study:	Thu Apr 30 21:20:03 IST 2015
Project Name:	Galway PH Retrofit - simple LCC
Project Location:	U.S. Average
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	D Coyle
Comment	Comparison with Excel spreadheet tool
Base Date:	April 1, 2013
Service Date:	April 1, 2013
Study Period:	30 years 0 months(April 1, 2013 through March 31, 2043)
Discount Rate:	4%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$110,510	-$110,510
Future Costs:			
Energy Consumption Costs	$141,854	$15,857	$125,997
Energy Demand Charges	$0	$0	$0
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$5,697	$11,246	-$5,549
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$24,689	$24,689
Subtotal (for Future Cost Items)	$147,550	$2,414	$145,136
Total PV Life-Cycle Cost	$147,550	$112,924	$34,626

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$120,447
- Increased Total Investment	$85,821
Net Savings	$34,626

Savings-to-Investment Ratio (SIR)

SIR = 1.40

Adjusted Internal Rate of Return

AIRR = 5.18%

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Simple Payback occurs in year 18

Discounted Payback occurs in year 28

Appendix H BLCC5 Cost Analysis Report - Case study dwelling - B3 'Shallow Retrofit'

NIST BLCC 5.3-13: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Base Case - "Do Nothing"

Alternative: Shallow Retrofit - to B3

General Information

File Name:	/Applications/BLCC5/projects/Galway PH LCCA/Galway PH LCC Final.xml
Date of Study:	Thu Apr 30 21:25:45 IST 2015
Project Name:	Galway PH Retrofit - simple LCC
Project Location:	U.S. Average
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	D Coyle
Comment	Comparison with Excel spreadheet tool
Base Date:	April 1, 2013
Service Date:	April 1, 2013
Study Period:	30 years 0 months(April 1, 2013 through March 31, 2043)
Discount Rate:	4%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$57,441	-$57,441
Future Costs:			
Energy Consumption Costs	$141,854	$48,224	$93,630
Energy Demand Charges	$0	$0	$0
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$5,697	$8,409	-$2,713
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$12,833	$12,833
	------------	------------	------------
Subtotal (for Future Cost Items)	$147,550	$43,800	$103,750
	------------	------------	------------
Total PV Life-Cycle Cost	$147,550	$101,241	$46,309

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$90,917
- Increased Total Investment	$44,608

Net Savings	$46,309

Savings-to-Investment Ratio (SIR)

SIR = 2.04

Adjusted Internal Rate of Return

AIRR = 6.50%

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Simple Payback occurs in year 14

Discounted Payback occurs in year 19