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Achieving Nearly Zero Energy Buildings - A Lifecycle Assessment Approach to Retrofitting Buildings

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Summary

It is now widely recognised in the academic and business worlds that energy efficiency in buildings provides significant environmental and economic opportunities, but also challenges. The building sector offers considerable opportunities to reduce Europe's energy consumption and carbon emissions. With the percentage of new buildings representing 1% of the total building stock and the low efficiency levels of the older building stock, retrofitting is recognised as the most immediate, pressing, and cost effective mechanism to reduce energy consumption and carbon emissions in the building and construction sector. It is necessary to double or triple the current retrofitting rate to reach EU short and long term energy reduction goals. However, given the age, diversity, size of the Irish and EU building stock, and the economic variables associated, retrofitting to meet sustainability targets on time represents a big challenge. This paper focuses on the current findings on the most effective energy measures for building retrofitting and the limitations in research on the retrofitting of buildings. Moreover, the paper discusses how the currently on-going research project nZEB-RETROFIT in the National University of Ireland, Galway can address these issues.

Keywords: Retrofit, Materials Technology, Lifecycle Assessment, Sustainability, Nearly Zero Energy Buildings

1 Introduction

1.1 Background

People spend approximately 90% of their lives indoors [1]. Thus, it is very important to maintain safe, healthy and comfortable living conditions in buildings. However, it is now widely acknowledged that a substantial proportion of energy is required to maintain these conditions in buildings. About 40% of the world's energy consumption and approximately a third of greenhouse gas (GHG) emissions are associated with buildings [2].

In the European Union (EU), the improvement of building sector's energy efficiency is among the main priorities of the Energy Performance of Buildings Directive (EPBD) introduced through the legislation in 2002 [3] and 2010 (recast) [4]. This legislation tightens the energy performance standard requirements of the European building stock with the aim of reducing the gap between the practices in the EU Member States. The recast directive [4] requires that all new buildings and existing buildings that receive significant renovations are nearly zero energy buildings (NZEB) by end of 2020. All public buildings are required to be NZEB by the end of 2018. The recast directive [4] defined an NZEB building as a building that has a very high energy performance. The nearly zero or low amount of energy required

should be covered to a very significant extent by energy from renewable resources, including those produced on site or nearby.

Further improvements in the energy efficiency of the European building sector include the 2007 EU '20-20-20' [5] initiative. This initiative requires Member States to cut their emissions, source their power requirements from renewables and improve energy efficiency by 20% from 1990 levels by 2020. Thus, EU legislation stipulates a significant amount of work to be done on the building stock in order to meet these targets. The EU is committed to reducing greenhouse gas emissions to 80 - 95% below 1990 levels by 2050 [6]. As the percentage of new buildings relative to existing buildings is increasing at a rate of only 1% per year [7] and a significant proportion of the old buildings stock will still be standing in the future, retrofitting is recognised as the most immediate, pressing and cost effective mechanism to reduce energy consumption and carbon emissions in the building and construction sector [8]. It is necessary to double or triple the current retrofitting rate of 1.2 - 1.4% per annum in order to reach the EU short and long term goals for energy and carbon reductions [9].

1.2 Overview of Irish housing stock and construction sector

The total number of dwellings in Ireland in the most recent 2011 Census was 1,994,845 [10]. The Irish housing stock has been ranked the youngest of all of the EU Member States [11]. However, over a third of the Irish dwellings were built before 1980 (Figure 1).

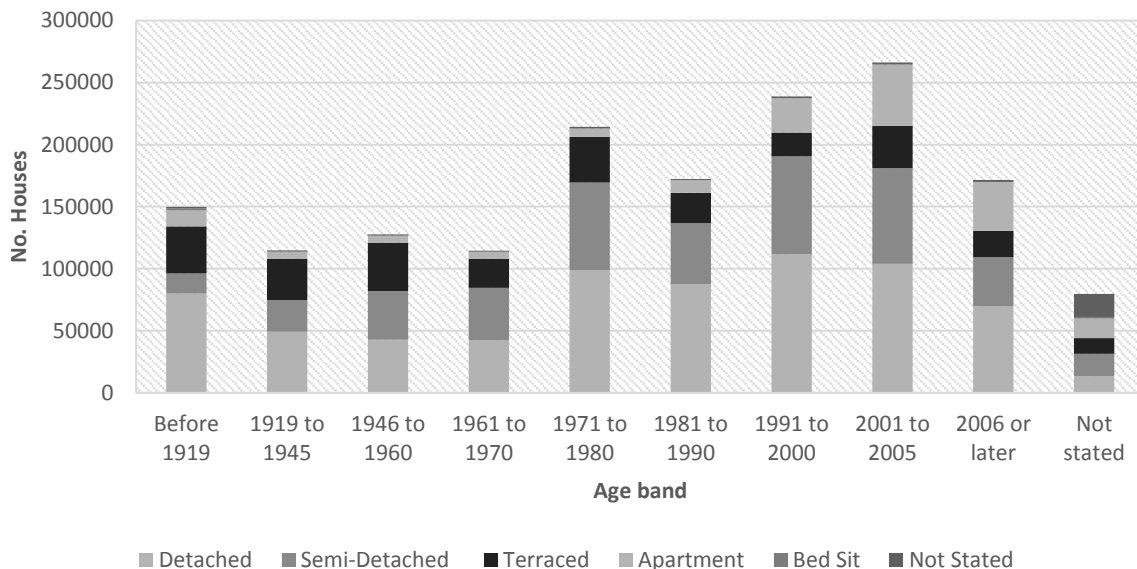


Figure 1: Age bands of Irish housing stock [10]

The type of dwelling (e.g. apartment, detached, semi-detached, terraced, etc.) is an important factor in terms of its energy consumption. Apartments are generally smaller consumers of energy compared to detached houses, but only represent 11% of the Irish housing stock. This is among the lowest in Europe [7], but the growth rate of apartments in Ireland is increasing (Figure 1). Detached houses are the most common type of dwelling in Ireland (Figure 1 and 2) and represent 42% of the Irish housing stock. These are primarily located in rural areas (72%) and are larger than the average European house. The houses located in rural areas use solid fuels or oil based heating systems as their scattering means they are not connected to the national gas grid [11].

The Building Energy Rating (BER) assessment system was set up due to the requirements of EPBD 2002 [3]. A BER is an energy label which rates the energy performance of buildings on a simple scale of A to G. It is based on the characteristics of the building and is not dependent on the behaviour of the occupants [12]. An A rated dwelling equates to the most operational energy efficient building. The primary energy consumption in a building of A1 and G ratings are 25kWh/m²/yr and 450kWh/m²/yr, respectively. Thus, the primary energy consumption of an A1 is approximately 5% of that of a G rated building. One in eight homes in Ireland is rated at F/G with only 0.1% of A-rated buildings.

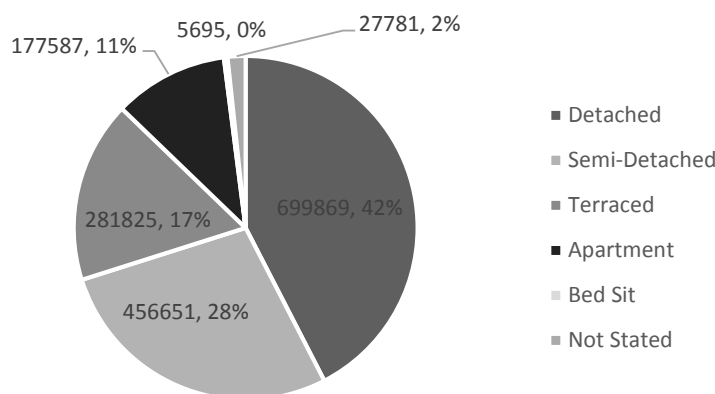


Figure 2: Residential housing stock by dwelling type

Thus, given the above and the fact that thermal performance standards were not introduced until the Building Regulations of 1979 [13], it can be seen why the Irish housing stock is among the poorest in Europe in terms of energy efficiency [10]. Therefore, the residential sector is a key area where Ireland can significantly reduce its energy consumption and carbon emissions in order to meet the mandate set out by the EU [5], [6]. The Irish residential sector accounts for 27% of the country's energy use, emits 10.5 million tonnes of CO₂ annually and is expected to contribute 35% of the energy savings required by the EU [11].

Compared to year 2006, when the Irish construction sector reached its peak levels, the number of people working in this sector had fallen by just over 56,000 in 2011 [14]. Given Ireland's recent austerity budgets, unemployment rates and emigration figures, a recovery is yet to have materialised. In order for the Irish construction sector to have a successful recovery, innovation is required. Areas of innovation in construction include prefabrication and modularisation, Building Information Modelling (BIM), materials innovation and smart infrastructure. Those are essential for the sustainable development of the Irish construction sector and should play a key role in the retrofitting of the Irish housing stock.

However, given the age, diversity, size of the Irish and EU building stock, and the economic variables associated, retrofitting to meet sustainability targets on time represents a big challenge. This paper highlights the findings on the most effective energy measures for building retrofitting, the limitations in research on the retrofitting of buildings and discusses how the currently on-going research project nZEB-RETROFIT [15] in the National University of Ireland, Galway can address these issues through a multi layered approach.

2 Overview of current research

Given the high variability of the characteristics of the Irish and EU building stock, there are many possible strategies to retrofitting a building to a higher energy standard. Thus, in order to achieve a NZEB, the most effective energy saving measures are needed. There are several published studies on the retrofitting of buildings. These studies focused on the evaluation of retrofit measures for buildings in terms of their energy savings, economic cost, lifecycle energy, carbon and cost as well as their influence on the occupant's thermal comfort.

2.1 Operational energy, carbon and cost analysis

The reviewed literature for the evaluation of energy, carbon and economic savings through the retrofitting of buildings have a common methodology. This involved the identification of common buildings and characteristics that best represent the housing stock of their respective countries using single [16], [17], [18], [19], [20] and multiple [21], [22], [23] case studies. Software tools were used to evaluate the effect that proposed multiple retrofit actions had on the energy consumption of buildings. These retrofit actions were then ranked in terms of either their energy, carbon or cost savings.

Wang & Holmberg [21] found the use of heat recovery ventilation, external and attic insulation to commonly yield the greater energy savings for residential buildings. Whereas, the upgrading to sensor controlled high efficiency lighting and improving the air tightness were the most common cost effective measures. The difference of energy savings in light (measures with high energy saving impacts) and advanced (measures with high and low energy saving impacts) retrofitting of the buildings was found to be between 36-54%. However, advanced retrofitting did not always yield long term economic profits for some archetypes. Furthermore, the findings of a comprehensive investigation into the retrofitting of eleven multi-family found that the highest energy savings were achieved with the upgrading of the building envelope and ventilation systems. The use of plant (PV, solar thermal panel) and adjusting the temperature set points were considered to be the substantially profitable retrofit measures [22].

Capeluto & Ochoa [16] identified the improvement of either the glazing or ventilation to be the optimal single retrofit option for an apartment in northern and central European climate zones. A combination of either shading and glazing or ventilation and glazing were the most effective combination of retrofit actions in terms of energy savings. A study into the retrofitting of a Danish apartment built in 1896 using varying combinations of insulation, window and HVAC retrofit options showed that a NZEB cannot be achieved without the use of renewables in the retrofit [17]. Eight of the simulated retrofit measures were installed in the apartment. Despite this, only the theoretical operational energy post retrofit was provided.

Morelli et al. [24] followed up on this with a method for determining an economic optimal combination of energy saving measures based on a cost of conserved energy (CCE) method. However, the methodology considered each of the retrofit options as individual components and did not account for the influence each of the components had on the other in terms of energy savings. The use of insulation was the most cost effective measure on an apartment building but it was found that predicting the price of future energy costs had a significant effect on the results. A study involving five residential buildings in Belgium [23] indicated that it was better to invest in the thermal envelope of the building first, then the heating system and then renewable technology.

A study of a residential building in a central region of Portugal found that there existed a threshold up to which energy savings might be obtained with a small retrofit and any further improvement required a substantial investment cost [18]. Building upon the research, the authors found that achieving higher energy savings or lower costs with a combination of retrofitting options did not necessarily lead to better thermal comfort for the residents [19]. Tronchin et al. concluded it was more expensive to invest in insulation than in heating plant, as retrofit measures [20].

2.2 Lifecycle energy, carbon and cost analysis

The previously discussed studies focused on the operational energy and cost savings that retrofitting measures would achieve. They did not evaluate the energy investment required to upgrade the buildings to a lower energy standard and if the operational savings were offset to a different stage of a buildings lifecycle. Lifecycle studies on building retrofits have been conducted previously, e.g. [25], [26], [27], [28]. These studies generally used one of two methods. The first involved defining the life cycle boundary limits from when the building was originally constructed and the calculation of the embodied energy (EE), embodied carbon (EC), operational energy (OE) and operational carbon (OC). The OE was simulated using building energy simulation software, e.g. EnergyPlus. The investment of EE in retrofit measures to reduce the OE/OC was used to determine a new life cycle energy and carbon for the building and to see if the reduction in OE/OC was not offset in EE/EC to a different stage of the lifecycle [25], [27]. The second method used in the lifecycle studies was similar to the first one with the only difference in relation to the life cycle boundary limits. The life cycle of the building was taken to start before the retrofit measures were applied to the building, meaning the EE related to the original construction of the building was not quantified [26], [28].

A cradle-to-grave life cycle analysis by Beccali et al [25] of a house retrofit in Italy showed that an increase in embodied energy investment led to a reduction in the OE of the building. The retrofit of a residential building in Canada showed that the environmental upfront cost of retrofit was paid back within two years of the retrofit [27]. Despite the retrofit measures being installed, there were no residents inhabiting the house; thus, the measurements of the energy consumption were only simulated and not physically measured.

Various retrofit options were applied to seven different public building typologies in seven different locations across Europe in one particular study [26]. Each building had a different combination of retrofit actions applied to it, which made the comparisons difficult. However, based on the energy savings and avoided Global Warming Potential (GWP), the most significant effects were related to the improvement of the thermal envelope. The OE before and after retrofit was monitored. However, the study did not discuss whether simulations of each of the buildings were carried out to determine the theoretical energy savings of the retrofit measures.

Lower life cycle energy and GWP could be achieved through new builds according to a study of Canadian residential houses [28]. However, only basement, attic insulation and air leakages (or a combination of these) were the considered retrofit options with the basement insulation providing the greatest energy savings. On the other hand, retrofitting the existing building in this study was the best option instead of constructing a new building in terms of having the lowest EE and lifecycle economic costs.

3 Methodology

The common conclusion emerging from the literature review to date for retrofitting buildings in terms of energy efficiency was that it is best to first improve the thermal envelope, then the heating system and then invest in renewables. However, some studies ranked these energy savings measures in different orders. There are many factors to consider for the reasoning behind this. One is that no two buildings are the exact same. Factors such as the buildings age, location, orientation, human behaviour, type of retrofit measure can have a bearing on the results of the energy efficiency assessment.

Thus, the work presented in this paper uses a systematic method which takes into account climatic conditions of the region where the case studies were located in order to make appropriate comparisons to see if the findings are applicable to the housing stock in Ireland (Table 1). In this method, the type of climate zone is based on the amount of hot degree days and cold degree days [29]. Taking 18°C as the base temperature for all climate types, the limits of each zone are shown in Table 1. Heating degree days (HDD) and cooling degree days (CDD) are a measure of how much (°Celsius) and for how long (days) outside air temperature was lower and higher than the base temperature. Using information gathered from an online degree day database [30], climate zones were assigned to each of the case study locations.

Out of 13 studies reviewed (Table 2), it can be seen that Zone D and E were the most common climate zones studied in the reviewed literature. As the Irish climate falls within Zone E, it is expected that a similar trend would follow for retrofitting Irish housing stock, where it is best to focus on the improvement of the thermal envelope first, then on the heating system and finally invest in renewable technologies in order to achieve a NZEB. This would particularly apply to the older Irish housing stock built before 1979 given its poor insulated properties, large floor areas and solid/oil fuel based heating systems.

However, out of 13 studies reviewed (Table 2), only four of the studies had calibrated their computational models against billed or measured data. Moreover, it was found that none of the reviewed case studies had monitored the impact installed retrofit measures had on the energy consumptions of the buildings and if they agreed with predicted computational results. Even though this paper does not imply that such published literature does not exist, it infers that there is a lack of research that involves validating predicted energy savings through installation of proposed retrofit actions and monitoring their influence on buildings' energy consumption. Studies have shown significant differences between simulated and actual building energy usage [31], [32]. This weakens the confidence and increases uncertainty in the accuracy of the theoretical energy savings presented by some published studies.

Table 1: Climate zone criteria [29]

Zone	Description	Requirements
A	$CDD \geq 500$ and $HDD < 1500$	High cooling needs, low heating needs
B	$CDD \geq 500$ and $1500 \leq HDD < 3000$	High cooling needs, medium heating needs
C	$CDD < 500$ and $HDD < 1500$	Low cooling needs, low heating needs
D	$CDD < 500$ and $1500 \leq HDD < 3000$	Low cooling needs, medium heating needs
E	$CDD < 500$ and $HDD \geq 1500$	Low cooling needs, high heating needs

Table 2: Overview of building retrofit case studies (with more than one retrofit measure adopted)

Ref.	Objective Functions	Retrofit Measure	Software/ Calibrated	Building type	Location/Climate Zone
[21]	Lifecycle cost, cost effectiveness, energy demand	Insulation, window, ventilation, thermal bridging, electricity source	IDA ICE, EnergyPlus	✓ 4 residential buildings	Stockholm: E
[16]	Energy efficiency and thermal comfort	Climate, colour, glazing, insulation, shading, ventilation, single vs combination	EnergyPlus	X Apartment building	Stockholm: E, Helsinki: E, Kaunas: E, Warsaw: E, Berlin: E, Vienna: E, Prague: E, London: E, Paris: D, Porto: C, Madrid: B, Rome: B, Athens: A
[22]	Lifecycle cost, primary energy use, CO2 emissions	Attic, external, floor and basement insulation, windows, doors, heat exchange and recovery ventilation system, water heat recovery, adjust indoor temperature, solar water panel, PV, energy efficient lighting and presence control	BV2 2010, IDA ICE	✓ 11 multi-residential buildings.	11 towns located in the Gavel Bourg region, Sweden: E
[17]	Energy savings	Insulation, windows, HVAC system, roof	BE10-one zone model	✓ Apartment building	Copenhagen, Denmark: E
[33]	Heating Load	Insulation thickness, core and perimeter temperatures,	EnergyPlus	X Residential building	Toronto, Canada: D
[20]	Cost optimal retrofit option	Wall, floor, roof insulations, windows, heating technology and energy carrier	UNI/TS 11300	X Residential building	Ravenna, Italy: B
[19]	Retrofit cost, energy savings, thermal comfort	External wall insulation, roof insulation, window types, solar collector installation	Trnsys, GENOpt, MATLAB	X Residential building	Central Portugal: B
[18]	Retrofit cost, energy savings	External wall insulation, roof insulation, window types, solar collector installation	RCCTE, MATLAB	X Residential building	Central Portugal: B
[23]	Retrofit cost	Wall, roof, floor insulation thickness, glazing type, space heating system, solar and PV panels	EPR	X 5 residential buildings	Belgium: D

[25]	Lifecycle Energy, CED ^a , GWP ^b , ODP ^c , AP ^d , EP ^e , POCP ^f	Insulation, Condensation boiler, PV	Trnsys	✓	Residential building	Palermo, Italy: A
[26]	Lifecycle energy, carbon and savings of building retrofit actions	Wall, roof and floor insulation, windows, lighting, boiler, heat pump, heat recovery, CHP, PV, solar thermal, wind turbines, ventilation	N/A		7 public buildings	Stuttgart: E, Hol: E, Plymouth: D, Vilnius: E, Brno: E, Provehallen: E, Borgen: E
[27]	Lifecycle energy, carbon and energy footprint	Insulation, windows, envelope panels, flooring, wall studs, communication and electrical wiring, duct work, heat pump, solar thermal	Hot 2000	X	Residential building	Kitchener, Canada: B
[28]	Lifecycle energy, environmental and economic	Attic insulation, basement insulation, air leakage	Athena-EE, Hot2000 – OE	X	Residential building	Toronto, Canada: D

a=Cumulative Energy Demand, b=Global Warming Potential, c=Ozone Depletion Potential, d=Acidification Potential, e=Eutrophication Potential, f=Photochemical Ozone Creation Potential

Stakeholders (government agencies, property management companies, local authorities, householders etc.) need to be able to accurately quantify the potential energy, carbon, cost savings, payback time and risk involved in retrofitting strategies of building stock in order to achieve NZEB requirements. This is especially true for the retrofitting of the Irish housing stock given its high proportion of one-off houses and the amount of different energy saving measures currently available on the market. However, the timeframe for the development of innovative technologies and business models to meet the EU's 2050 targets has narrowed to less than ten years [34]. The nZEB RETROFIT project aims to tackle these retrofitting issues through a multi-layered approach.

3.1 nZEB-RETROFIT

The work presented here is part of the nZEB-RETROFIT project: Achieving nearly zero-energy buildings – A lifecycle assessment approach to retrofitting existing buildings. nZEB-RETROFIT is an ongoing research project in the National University of Ireland, Galway, Ireland which aims at tackling the issues relating to the retrofitting of the building stock. The overall goal of the project is to examine the effectiveness of innovative building structural elements and systems, regarding their structural, environmental and energy performance in retrofitting of existing buildings.

The goals of the project will be achieved through laboratory scale research, on site full scale research based on real-time data, numerical modelling and desktop research using a multi layered approach (Figure 3).

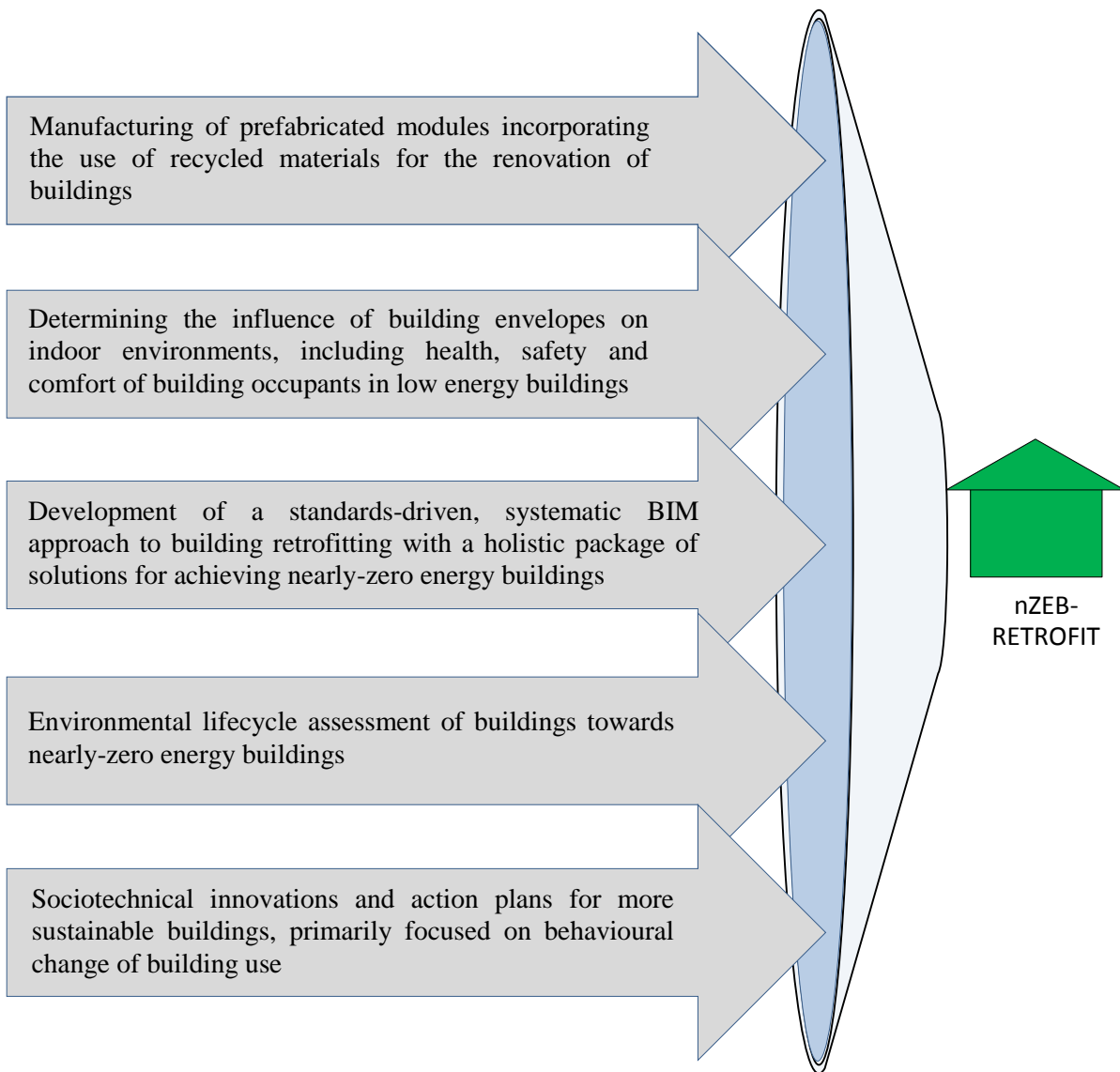


Figure 3: Multi-layered approach of the nZEB-RETROFIT project

4. Conclusion

Retrofitting is recognised as the most immediate, pressing and cost effective mechanism to reduce energy consumption and carbon emissions in the building sector for Europe to reach its short and long term goals. However, given the age, diversity, size of the Irish and EU building stock, and the economic variables associated, retrofitting to meet sustainability targets on time represents a big challenge.

Research into the most effective retrofit measures revealed that for climates where buildings require low cooling and high heating demands the best practice is to first improve the thermal envelope, then the heating system and then increase the use of renewable technologies in order to achieve a NZEB. However, only few studies calibrated their building energy simulation results with the physical data in order to reassure the quality of computational results. Moreover, it was found that none of the reviewed case studies had monitored the impact installed retrofit measures had on the energy consumptions of the buildings and if they agreed with predicted computational results. Thus, there is lack of knowledge and tools available for decision makers in the retrofit stakeholder value chain to make crucial decisions in regards to the renovation of buildings to low-energy standards.

With the ambitious targets set out by the EU for each of its Member States to reach, the rate of building retrofits is required to double or triple in order to reach these goals. It is therefore vital not to repeat the mistakes of the past. Proper planning is required to produce high quality solutions and construction practices within the industry to achieve the NZEB requirements set out by the EU. In order to do this, key decision makers in the stakeholder value chain require the knowledge, tools and confidence in order to develop high quality solutions to renovate buildings to the required NZEB standards.

The nZEB RETROFIT research project aims at tackling some of these challenges through its previously discussed multi-layered approach. The expected impacts of this research include strengthening the economy by introducing innovative products and tools for retrofitting buildings, creating high value jobs in the stagnant construction sector, and enhancing health and quality of life of the building occupants.

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