Sustainable Energy Authority of Ireland

National Energy Research, Development & Demonstration Funding Programme

FINAL REPORT

SECTION 1: PROJECT DETAILS – FOR PUBLICATION

Project Title	Hygrothermal assessment in cold roof buildings with reduced ventilation
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	Name	**Organisation**
Project Partner(s)		
Collaborators		

Project Summary (max 500 words)

This project advances our understanding of the environmental conditions of a dwelling's attic space in Ireland incorporating a dormer structure and subsequent life cycle costs (LCC) assessment for a deep energy retrofit.

Thermally inefficient buildings are prevalent throughout Ireland creating a barrier to ending fuel poverty and reducing CO_2 emissions. The building sector in the EU and USA typically accounts for up to 40% of total energy consumption, with 69% attributed to space heating. Dwellings that are poor at conserving energy can lose up to 30% of their heat through the roof. Retrofitting homes with energy saving technology can provide significant benefits to the consumer, environment and economy. The issues associated with dormer attic retrofit occur due to the restricted space between the roof rafters and plasterboard ceiling of the dormer room. Meeting the current building regulations requires a significant depth of insulation that is typically not available where the ventilation requirement must also be considered. The aim of this project is to investigate the relationship between insulation thickness, humidity and temperature with reduced ventilation levels. This was assessed through simulation of post retro fit of dormer attics under varying regional climate conditions, operating conditions for the interior living space and attic space and envelope material assemblies. In addition, the difference in energy consumption of the dormer and non-dormer of various building archetypes was assessed and the pre and post retrofit values used for a LCC analysis.

This project will help to grow Ireland's national capacity to develop and apply world-leading energy RD&D. The outcomes of the project included new human capital in the form of post-doctoral level expertise in the area, as well as developing guidance and support to policymakers and public

bodies on the potential impacts of energy retrofitted dwellings on the Irish building stock, the Irish construction industry, and on fuel poverty.

Keywords (min 3 and max 10)	Energy Efficiency, Dormer Attic, Interstitial Condensation, Ventilation, Building Energy Ratings, Retrofit

SECTION 2: FINAL TECHNICAL REPORT – FOR PUBLICATION (max 10 pages)

2.1 Executive Summary

This research investigates the impacts of energy retrofit measures to domestic building fabric for the case of dormer attic rooms under Irish climate conditions, on the hygrothermal performance of the attic space and potential for mould growth. These alterations to the building envelope have significant energy conservation benefits but their hygrothermal performance, particularly in the context of dormer-style attic rooms, is less understood and the return on investment, post retrofit requires investigation. This research used traditional housing in Ireland with pitched roofs as the case study to examine changes in the hygrothermal environment following energy retrofits. The study compared the mould growth index (MGI) of roof rafters under different energy retrofit scenarios to understand the effect of adding a habitable dormer-style room on the house's mould growth risk. The results show that adding an occupied dormer room can increase the MGI of spruce rafters from below 1 to around 5.2 at 0.2 air changes per hour (ACH) of infiltration. In most scenarios, a ventilation rate lower than 1 ACH cannot prevent the MGI of rafters from reaching the critical threshold 3 for dormer-style attic rooms, unless a 1mm vapour barrier is added. A ventilation rate over 5 ACH is adequate to limit the mould growth risk, but mechanical ventilation may be required to achieve this level of attic ventilation. This study enhances understanding of the relationship between attic ventilation rates and the risk of mould growth post energy upgrade of dormer style rooms, a common dwelling across Northern Europe and further afield.

In addition, this research also evaluated the potential energy and whole life cycle cost (LCC) savings arising from the deep energy retrofit of residential buildings. The cost optimal model was determined for material upgrades and the addition of an air-to-water heat pump resulting in net zero energy buildings (nZEB) for existing structures. The analysis showed whole LCC savings post retrofit for a dwelling insulated at the ceiling/rafter and installation of a heat pump amounts to a savings of €80,928 for an uninsulated dwelling pre-retrofit, rising to €116,691 for dwellings with a dormer. Partially insulated dwellings, pre retrofit all resulted in a favourable return on investment, ensuring a cost optimal model. Although a sensitivity analysis found that high discount rates, fuel prices and increasing capital costs can negate the return on investment. Finally, at a national level energy saving of 13.08 TWh by 2030 could be realised if the Climate Action Plan 2023 retrofit targets are adhered to for the Irish case study. In addition, LCC savings could be valued at €16.4 billion. Where retrofit uptakes only amount to slightly more than half the target aims, this incurs energy savings of 5.68 TWh and €8.21 billion.

2.2 Introduction to Project

2.2.1 Hygrothermal modelling (WP3)

Hygrothermal assessment is used to determine the long-term risk of moisture damage and mould growth within building envelope assemblies in various climate regions throughout the world for various types of residential [1] and commercial buildings [2] and in historic sites [3,4]. Models of this process use transient coupled whole building simulations of heat and moisture transport in multi-layered building components to forecast the risk that excessive moisture poses [4]. This can inform the design of appropriate control measures. For example, Desai et al. [5] investigated the MGI of a low-rise commercial building in a warm and humid climate, and for an autoclaved aerated concrete wall assembly, an MGI above three over the course of a single year was observed. This suggested an MGI of 6 would occur over the building lifetime. Arregi and Little [6] examined a single case study for a wall structure in mild temperate climate conditions and found that improper design of internal insulation can lead to mould growth and a need for adequate ventilation and vapour barriers [6].WP3 comprised a hygrothermal analysis of a dwelling's attic space and the impact on the roofing assembly of post-insulation retrofit, with and without a dormer-style attic room, when subject to temperate maritime climate conditions. We examine the impact of increased surface area exposure to heat loss in the attic space. The research aimed to identify the ventilation requirements for occupied dormer-style attic spaces undertaking energy retrofits as current building regulations do not allow minimum passive ventilation requirements and insulation depths, both to be met where insulation is applied to the rafter depth. The findings of the research identify a route to enabling energy retrofit of dormer-style dwellings to aid in meeting national and international climate targets for domestic building energy.

2.2.2 Bottom-up energy modelling and LCC analysis (WP4)

WP4 used a bottom-up modelling methodology, as this approach evaluated the national residential energy consumption by disaggregation of national stock into individual dwellings representative of the residential building archetypes, roofing structures and energy rating. The bottom-up approach has proven to effective at analysing policy measures by extrapolation to a national level targeting energy efficiency improvement to a dwelling. Typically, this analysis is performed based on retrofit upgrades assessed with the building performance evaluation software packages such as Standard Assessment Procedure (SAP) in the UK [7] or in Ireland, Dwelling Energy Assessment Procedure (DEAP) [8]. Dineen et al. [9] created 175 building archetypes based on building energy ratings (BER), prevalent dwelling types and wall construction design. While the benefits of the retrofitting have been widely acknowledged, their exists several barriers that have prevented a larger uptake by homeowners or businesses. In the residential sector a lack of financial incentives, large upfront capital costs, technical issues, lack of awareness, limited workforce capacity, and inefficient management are some of the issues commonly identified [10]. Providing more information on the value of deep energy retrofits by demonstrating cost optimal models to consumers can help to improve uptake and address some of the barriers.

WP4 aims to develop representative building archetypes of the national residential building stock that capture the various roofing structures and the variation in energy consumption between dormer and non-dormer dwellings in the EU. The bottom-up modelling approach will be used to assess the impact of retrofit measures outlined by upgrading dwellings to a BER standard of B or cost optimal on the national residential dwelling stock under various levels of retrofit uptake. In addition, the installation of an air-to-water heat pumps will also be explored for A-rated dwellings and their influence on national accumulated energy savings and CO_2 emissions. The national energy savings were assessed, as homes with a dormer structure have been excluded from energy efficiency improvement schemes to date due to the retrofit capital costs outweighing the savings from increased energy efficiency (i.e., the cost optimal model) [11,12]. This occurs as the space between the roof rafters and dormer walls is too restricted to install the recommended depth of insulation in order to achieve the required U value without incurring significant capital costs. An assessment will also be conducted using LCC methods to explore if converting individual dormer and non-dormer dwellings into B-rated or A-rated dwellings from C-G rated homes is cost optimal. Finally, a similar approach to assessing the national energy savings based on retrofit measures will be applied to determining the accumulated national whole life cycle savings.

2.3 Project Objectives

The objective of the project is to address the issues associated with insulating dormer attics where the required specifications as per building regulations are not achievable in an economically viable fashion. Understanding the conditions which can lead to condensation if energy retrofit measures are undertaken is vital to ensuring that no long-term structural damage is caused. The development of this new understanding will facilitate the installation of insulation into restricted attic spaces which will benefit Ireland through decreased domestic energy usage and lower fuel costs. This will improve conditions in homes in poor socio-economic areas living in fuel poverty and reduce CO_2 emissions arising from the built environment. To achieve this aim, the following objectives were proposed:

1. Advance our understanding of the hygrothermal behaviour of dormer attics under varying Irish building design and climate parameters: pre and post retrofit
2. Demonstration of retrofit viability through energy and cost analysis of typical Irish dormer attics: pre and post retrofit
3. Understanding the trade-offs between condensation, ventilation and insulation thickness in restricted roof spaces
4. Dissemination and communication of potential new systems and guidance for the energy retrofit of dormer attics
5. To analyse the state of energy consumption and efficiency in European dwellings, particularly in Ireland, and to identify barriers that prevent the adoption of energy efficiency measures.
6. To develop representative building archetypes using a bottom-up modelling approach and assess the impact of energy retrofit measures and installation of air-to-water heat pumps on energy savings and CO2 emissions.
7. To conduct a Life Cycle Cost (LCC) analysis on retrofitted dwellings, providing recommendations to enhance the adoption of energy efficiency retrofits towards achieving a fully decarbonised building stock by 2050.

2.4 Summary of Key Findings/Outcomes

2.4.1 Key findings of WP3

This research uses whole-building simulation software to evaluate the hygrothermal performance of non-dormer and dormer roofs, assessing mould growth risks in a representative semi-detached house in central Ireland. Following initial validation of the simulation model using temperature and relative humidity (RH) sensor data from a case study building interior living and attic spaces, several scenarios (Table 1) including the addition of a dormer-style attic room were explored with different attic and indoor ventilation rates. The study also examined the impact of dormer window designs on mould growth, the influence of varying climate conditions across Ireland, from four different regional locations. Three indoor moisture levels were investigated in relation to varying ceiling leakage rates and investigated the impact of a vapour barrier. The research also included a long-term analysis over five years based on historical weather data, as well as a 30-year forecast. The study also factored in the energy consumption of mechanical ventilation where required under different retrofit scenarios to evaluate cost efficiency.

Innovation 1: Calibration of hygrothermal model for whole building model of a Irish residential building with sensor data from a field study. *The internal living space and attic space boundary conditions for the whole building hygrothermal model of a semi-detached dwelling were configured to match the temperature and RH outputs from the experimental data extracted over a 6-month monitoring period.*

Table 1: Description of different simulation cases and variables.

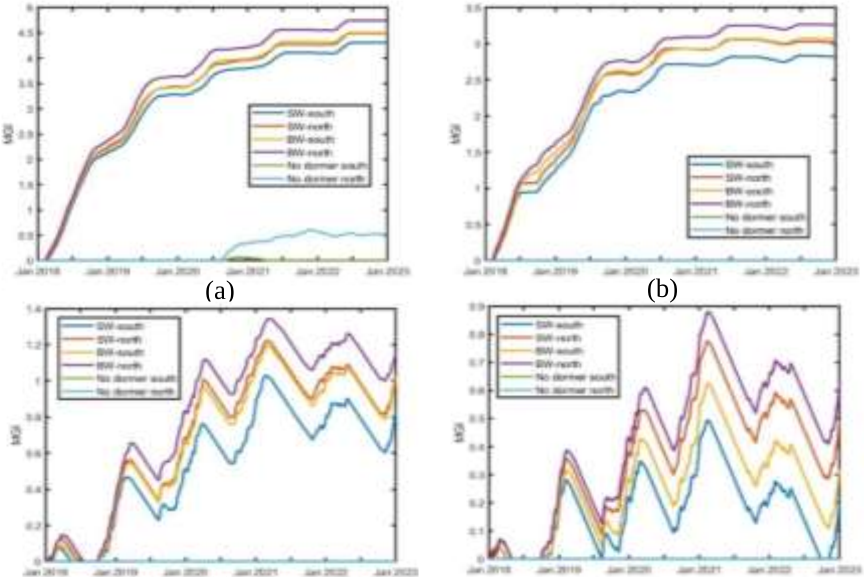
Case No.	Variable							
	Description	Climate	Attic ACH	Moisture level	Ceiling leakage	Window size	Period	Vapour barrier
1	Model Calibration	Midlands	Based on calibration data			No window	02/08/2022 to 22/02/2023	No
2	Different Attic designs	Dublin	0.2	No dormer	0.1	No window	5 years	No
			1	Normal level*	0.2	0.89 m^2		
			5		0.05	4.5 m^2		
			10					
3	Different regional climate	Dublin	0.2	Normal level	0.1	0.89 m^2	5 years	No
		Cavan	1					
		Cork	5					
		Galway	10					
4	Different internal moisture level	Dublin	0.2	Normal level	0.1	0.89 m^2	5 years	No
			1	Low level (-25 %)	0.2			1mm
			5	High level (+25%)	0.05			
			10					
5	Long-term MGI and cost assessment	Dublin	0.2	Normal level	0.1	0.89 m^2	30 years	No
			1					
			5					1mm
			10					

* Daily house moisture levels (4-person occupancy) Ground floor - 8583g Dormer - 3556g

Case 2, as illustrated in Figure 1, shows that the MGI of rafters in the roof of the retrofitted dormer significantly worsened compared to no-dormer cases. Both small window (SW) and big window (BW) scenarios saw an increase in MGI starting from March 2018, exceeding the critical threshold of 3 for non-occupied spaces by the end of the 5-year simulation in an unventilated attic (i.e., 0.2 ACH due to infiltration).

Notably, the northern rafters of the BW recorded the highest MGI of over 4.5, indicating an unviable attic design. The study also reveals that passive ventilation only marginally decreases MGI, and remains elevated over time, suggesting that passive ventilation of 1 ACH is insufficient to mitigate mould growth risk. Only with increased ventilation rates between 5 and 10 ACH is an acceptable MGI achieved. Such a level of ventilation, however, would require mechanical ventilation systems to keep the MGI under 3.

Innovation 2: Demonstration of the impact a dormer structure has upon the MGI of the roof rafters in comparison to the negligible effect on the non-dormer structure and the quantification of the ventilation requirements. *The non-dormer attic is sufficiently ventilated through passive methods based but the dormer structure requires higher ACH which requires mechanical ventilation. The north facing rafters also suffered from higher MGI values with both a small and big window than the south.*



(a) (b)

(c) (d)

Figure 1 MGI of the rafter spruce for no dormer, small window (SW) and big window (BW) design strategies where (a)0.2 ACH, infiltration only, (b) 1 ACH, (c) 5 ACH, and (d) 10 ACH.

Case 3 results found that at an infiltration rate of 0.2 ACH, Dublin's MGI values are marginally lower than other areas. By 2022's end, Cavan has slightly higher MGI values than similar ones in Cork due to its greater humidity, while Dublin maintains the lowest humidity. Increasing ventilation to 5 ACH highlights a more significant deviation in Dublin's MGI values, dropping to 1. Galway's MGI briefly surpasses that of Cavan and Cork at the same ventilation level, a trend that repeats when ventilation rises to 10 ACH. The seasonal influence is more noticeable as ventilation exceeds 5 ACH, with MGI values showing a winter increase, a spring peak, and a summer decline. Analysing seasonal humidity and temperature data, winters and springs exhibit higher mould growth risk due to lower temperatures and higher humidity. Dublin's significantly lower humidity explains its lower MGI value. In contrast, Galway's climate, with its higher humidity and slightly warmer temperatures during these seasons, appears more conducive for mould growth, resulting in its MGI value exceeding other locations.

Innovation 3: Regional analysis of MGI values across Ireland and influence of their respective climate conditions with varying ventilation rates. *The results found that the wetter climate on the west coast with higher humidity levels and warmer in the winter and spring resulted in a greater susceptibility to mould growth compared to the colder dryer spells in Ireland's eastern region.*

Case 4 of the study examines how internal moisture loads, ceiling leakage, and the addition of a vapour barrier impact MGI in roof sections. The findings suggest that both increased internal moisture load and ceiling leakage can lead to higher MGI, indicating a heightened mould growth risk. This risk, however, can be mitigated by increasing ventilation to 1 ACH or introducing a 1 mm vapour barrier, which significantly reduces MGI values across all humidity levels as shown in Figure 2. Particularly, with 1 ACH ventilation and a vapour barrier, all MGI values fall below the critical threshold of 3. Furthermore, the study finds that under 1 ACH attic ventilation and 0.2 ACH dormer infiltration, plasterboards have higher MGI than spruce rafters, but is reduced by adding a vapour barrier and/or increasing dormer ventilation to 1 ACH.

Innovation 4: Vapour barrier negates the need for mechanical ventilation if the interior living spaces are adequately ventilated. *The results show the synergistic relationship between the indoor living space and the attic environment where reducing the moisture transfer through the ceiling and ventilating the dormer room reduces the MGI of the ceiling plasterboard and roof rafters.*

The long-term forecasting simulation in Case 5 found that the MGI reaches a steady state at different times depending on ventilation rates. For an unventilated attic space with 0.2 ACH on the north face, significant changes cease after seven years, with the MGI settling just above a critically dangerous level of 5. The south face shows a similar trend, albeit slightly lower, yet still at a structurally dangerous level. For an ACH of 1, the MGI hovers around the critical level of 3, suggesting that higher passive ventilation rates are required for long-term safety. Steeper changes in MGI are observed at lower ventilation rates before gradually stabilising. A more pronounced MGI difference between the north and south faces is found at a ventilation rate of 10 ACH. Stabilisation for higher ventilation rates occurs approximately five years into the assessment, with significant changes in MGI observed for 5 and 10 ACH, though these remain within structurally safe levels.

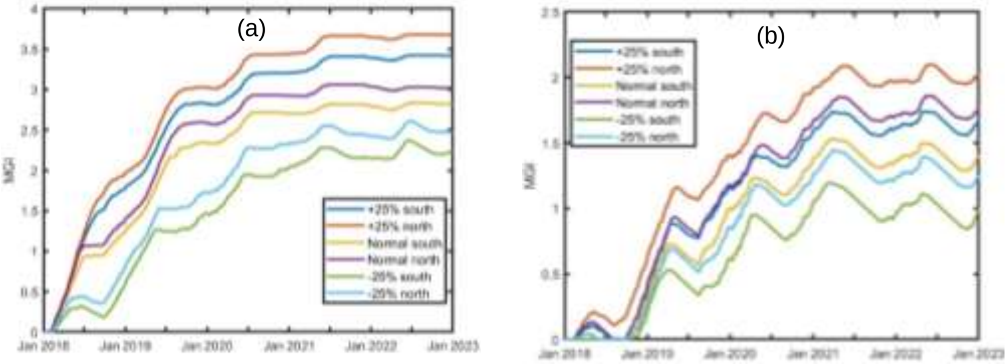


Figure 2 MGI for spruce Change with the dormer moisture level Dublin at 1 ACH and 0.1 ACH ceiling leakage with (a) No vapour barrier, (b) vapour barrier.

Innovation 5: Determination of the stabilisation of MGI using a long term forecast and maximum MGI. *The results illustrate the culmination of mould growth from years of exposure to Irelands climate and consequences of poorly designed indoor living spaces with regards to moisture transfer.*

Adding a vapour barrier in mechanically ventilated attics substantially reduces energy use and costs. The 10 ACH scenario with a vapour barrier is the most efficient, consuming only 80% of the energy of its counterpart without a vapour barrier. The installation of a vapour barrier leads to annual electricity cost savings of average annual savings of €17 in the 10 ACH scenario and €8 in the 5 ACH scenario. Importantly, the 10 ACH scenario demonstrates greater energy savings when a vapour barrier is added compared to the 5 ACH scenario, suggesting higher ventilation settings benefit more from this measure. Lastly, despite the initial expense, the payback period for adding a vapour barrier is 7 to 14 years. Over 30 years, the 10 ACH and 5 ACH scenarios save modest amounts of approximately €402 and €138, respectively, showing the long-term financial benefits of this energy-efficient solution.

Innovation 6: Vapour barriers result in greater energy savings for higher ventilation rates.

2.4.2 Key findings of WP4

The first stage of WP4 involved a simple study examining the optimum insulation thickness (OIT) and payback periods for retrofit upgrades by incorporating an LCC model with the degree day (DD) method for a residential roofing structure. Three fuel types (heating oil, gas and electricity) and insulations (rockwool, standard polyisocyanurate (PIR) material and a special but more expensive PIR material with lower thermal conductivity) were examined for three roofing configurations. The first roofing type was uninsulated, the second and third partially insulated prior to retrofit. The results found the standard PIR to be the most effective and also resulted in an OIT that produced U values around the regulated U values depending on DD value. The findings demonstrated the balance between the type of insulation used based on their cost and efficiency must therefore be sought when considering the appropriate retrofit measures.

Innovation 1: Analysis of OIT for various roofing configurations. *Building archetype models were created based on roofing structure, building type and energy rating. Building archetypes are also divided based on their building envelope dimensions and volumes extracted from NAS database.*

A more elaborate study was conducted next in WP4 using DEAP which established models representative of the Irish residential building stock, identifying considerable yearly primary energy use disparities due to varying building envelope dimensions and volumes and archetype across their respective BER ranges. For instance, models with attic dormer conversions experienced elevated thermal energy losses and heating transmission loads due to a larger surface area exposed to cold attic environments, leading to increased yearly energy use. As shown in Figure 3, the annual energy consumption of A-G-rated three storey room in roof (3S-RIR) detached dwellings ranged from 12.98 to 130 MWh/yr, compared to two storeys insulated at the ceiling (2S-Ce) detached dwellings, which ranged from 8.24 to 97.4 MWh/yr. As Building Energy Rating (BER) grades improve, this consumption gap diminishes. The lowest annual energy consumption was noted in terraced houses and apartments without a dormer, correlating with their smaller floor areas.

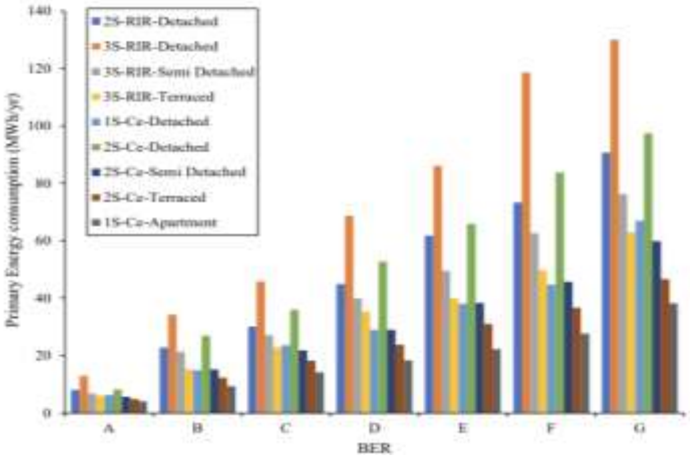


Figure 3. Assessment into the impact of the average internal building design on the primary energy consumption (MW/h) per annum of the various building archetypes with and without a dormer conversion across the entire BER grade range.

Innovation 2: Disaggregation of non-dormer and dormer dwellings by their thermophysical characteristics and individual annual primary energy consumption. *The building archetype models were created based on their roofing structure, building type and energy rating and are configured based on their building envelope dimensions and volumes extracted from NAS database.*

Innovation 3. Energy analysis based on building envelope dimensions, BER grade and roofing structure. *Dwellings with dormer conversions used more energy than non-dormers but the difference reduces with increasing BER standards. In addition, the detached building had the largest energy consumption, followed by semi-detached and then terraced, with apartments using the least energy.*

In terms of the economic return of material and heating system upgrades in detached dwellings, WP4 calculated the LCC pre- and post-retrofit. Two post-retrofit options were considered: a B-grade material upgrade and an A-grade upgrade with the addition of a heat pump. The capital costs for the 1S-Ce detached models ranged from €5,000-55,000 taken from Ó Broin et al. [8], which are indicative of the retrofitting costs in Ireland to upgrade dwellings to a B2 standard. The median cost of heat pumps was estimated at €15,000, and this cost was incorporated into all A-rated models in the LCC analysis. In cases like 1S-R and 2S-RIR, fabric capital costs were increased by 10% and 25% respectively, due to insulation thickness restrictions by the rafter and potential extra works to meet building regulations. The results revealed that even with a 25% increase in the material capital costs for 1S-RIR detached dwelling, the total savings after a deep energy retrofit are significant. Upgrading this dwelling from G-rated to A-rated results in lifecycle savings of €116,691 compared to €80,928 for a detached 1S-Ce. The overall LCC savings decrease for each building archetype irrespective of the roof structure as the Building Energy Rating (BER) grade increases. Payback periods varied, with 2S-RIR taking between 10-16 years and 1S-Ce between 12-20 years depending on pre retrofit BER. The study concluded that while these are not particularly attractive returns on investment for domestic consumers, government incentives could enhance financial viability. In a secondary lifecycle cost (LCC) analysis that focused on upgrades to B-rated dwellings excluding the installation of heat pumps, the results showed slightly longer payback periods and significantly lower total LCC savings post-retrofit compared to those of the A-rated dwellings with heat pumps. In addition, a sensitivity analysis showed cost optimal retrofit were susceptible to negative returns on investment with high discount rates, increased capital costs and rising heating oil rates and reduced electricity costs, where heat pumps are part of the retrofit measures.

Innovation 4: Higher initial investment, homeowners and social housing projects would get a better return on investment and more favourable payback periods if they upgrade existing dwellings with a heat pump to achieve an A-rated status. *LCC analysis demonstrated the viability of both a heating system modification through use of heat pump technology and material upgrade based on cost savings through lower energy consumption and a more efficient heating system. Payback period were shorter due to greater life cycle savings.*

Innovation 5. Return on investment for retrofit project highly susceptible to market conditions such as capital costs, energy prices and the discount rate. *Although the LCC analysis under the baseline 4% discount rate produced excellent returns on investment, especially for uninsulated dwellings to A rated, as the discount rate approaches 10% the projects become unviable.*

The previous analyses focussed on individual dwelling analysis. These models were then used to extrapolate to a national level, examining several retrofit scenarios based on the proposed retrofit targets from Ireland Climate Action Plan 2023. The results illustrated substantial variation in energy and CO_2 savings based on the rate of deep energy retrofits and the addition of heat pumps (Figure 4).

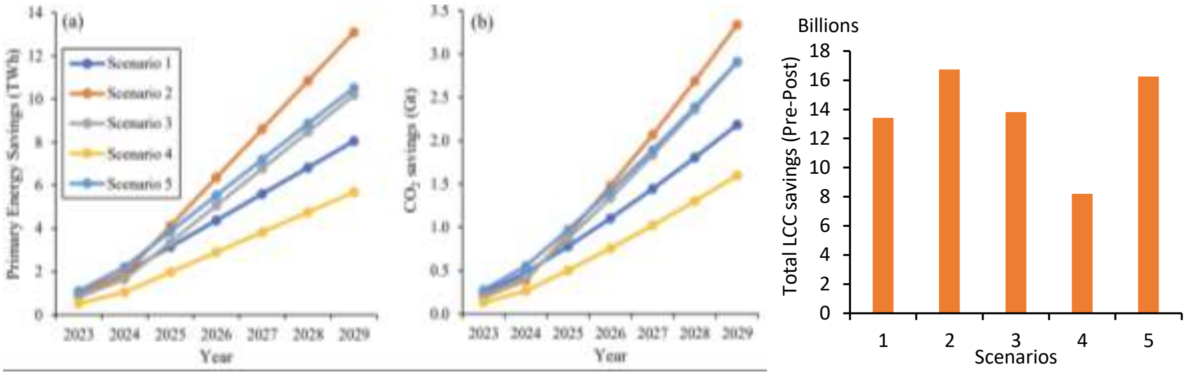


Figure 4 Figure 5 Accumulated (a) primary energy savings (TWh) (b) CO2 savings (Gt) (c) primary energy whole life cycle post retrofit monetary savings after twenty year project lifetime; accrued from fabric upgrade only (B-rated dwelling) and fabric and heat pump upgrade (A-rated dwelling) where; Scenario 1 (500,000-B, 0-A), Scenario 2 (200,000-B, 400,000-A), Scenario 3 (250,000-B, 250,00-A), Scenario 4 (200,000-B, 100,000-A) and Scenario 5 (500,000-B, 100,000-A).

For instance, Scenario 1, involving 500,000 material upgrades to B-rated dwellings without heat pumps, led to energy and CO_2 savings of 8.045 TWh and 2.182 Gt by 2029, while Scenario 2, meeting policy requirements with 200,000 upgrades and 400,000 heat pump installations, resulted in 13.08 TWh energy savings and 3.34 Gt of CO_2 savings. The accumulated LCC savings also varied significantly. For example, Scenario 3 resulted in approximately €0.4 billion more post-retrofit LCC savings than Scenario 1, despite a similar difference in accumulated energy savings. Remarkably, Scenario 5's LCC savings were only half a billion euros less than Scenario 2, despite a substantial difference in accumulated primary energy consumption, suggesting heat pump installations lead to greater savings, even with higher capital costs.

Innovation 6: National energy and LCC savings accrued from retrofit measures over a range of uptakes based on material and heat pump upgrades for dormer and non-dormer dwellings. *The number of retrofits carried out is vital to large, accumulated energy and whole LCC savings, but the proportion of heat pumps is also of importance. Ensuring heat pumps are part of the retrofit leads to the greatest energy savings at 13.08 TWh by 2030 and highest total LCC savings after a twenty-year period at €16.74 billion under the Climate Action Plans policy target.*

2.5 Project Impact

The end users that will be impacted by successful project completion include; domestic energy consumers, energy regulators, retrofit specialists, building regulation policy makers, insulation manufacturers, future research capacity, and the scientific community:

Economic impact

Improvements in the energy efficiency of domestic dwellings is a key objective for obtaining a sustainable housing infrastructure that will promote economic growth. The housing energy retrofit market has been identified as key to promoting a job led growth and ensuring our climate commitments are met. This project demonstrates the importance of introducing more homes into government grant schemes and cost optimal solutions for private owners of buildings with a dormer conversion that would not qualify for a full rebate. This would significantly increase the size of market for energy retrofits and create more opportunities for the creation of small and medium businesses in the building sectors energy retrofit market. In addition, the demand for skilled workers who can install insulation to current building standards will contribute to significant economic growth and provide more job opportunities regionally and nationally. Increasing the energy efficiency of homes will also have an additional benefit of increasing the value of the domestic dwelling. As the building stock is now graded based on their energy consumption and the building envelope thermal efficiency, the grade associated with the home is intrinsically linked to the economic value of the dwelling. An ESRI Energy Policy report found that homes with an A value relative to a D grade fetched a 9% premium on home sales [13].

Societal impact
The energy retrofitting of homes with dormer attics will provide a significant reduction to national greenhouse gas emissions within Ireland. This will occur through a lower usage of carbon-based fuel caused by the reduction in heat loss through the building envelope. The benefits will be seen in both energy and cost savings to the average household, increased thermal comfort of the indoor environment, and reduced local air quality issues. Currently the Program for Government recognises that increasing carbon tax could have a detrimental effect on those living in fuel poverty and mitigating measures are required to reduce this burden on low income families. Incremental increases in carbon tax are planned from now until 2030 as per the Climate Action Plan 2023, which will have a major impact on those living in dwellings with low BER grades. Unless significant actions are undertaken to increase the energy efficiency of every home in Ireland, an increase in the national average of citizens living in fuel poverty is inevitable as a result. This further highlights the importance of the outcomes of this project where improvements in the energy efficiency of dormer type dwellings with significant design challenges would be excluded from certain SEAI grants and aid schemes. Improving the BER grade is the first line of defence in reducing energy consumption, as the most cost-effective strategy is energy conservation.

Policy impact
The EU aims to reduce energy consumption of residential buildings through increasing the national building stock energy efficiency by 32.5%. This project is targeting a positive contribution to energy efficiency policy and reduction of Irish residential energy consumption. The project team consulted with policymakers on the project findings impact with regards to energy targets and implications on the Climate Action Plan 2023. In addition, building regulations were appraised for ventilation requirements and use of a vapour barrier in the dormer structure. To successfully achieve the 500,000 energy retrofit target to B2 standard and 400,000 heat pumps set out in the Climate Action Plan 2023, further support is required by the state and a policy measure on providing local authority green loans or similar at low interest rates could result in a higher deep energy retrofit uptake by homeowners. The project detailed through the inclusion of building archetypes with non-dormer and dormer structures, the national impact of different levels of retrofit uptakes on national energy consumption and LCC savings.

Scientific impact
A positive scientific impact was created through the generation of new knowledge in the area of building science, energy economics and sustainable infrastructure. There are a limited number of studies that have definitively analysed the effect ventilation plays upon hygrothermal conditions within a dormer attic, especially in temperate oceanic climates. A conference and journal paper have been produced detailing the impact of Ireland's climate conditions on a post retrofit dwelling interior and attic space for dormer and non-dormer dwellings. On the energy economics side, a conference paper and journal paper have also been created outlining the impact of national retrofit measures and LCC impact pre and post retrofit. The findings have advanced our understanding of the residential energy sector based on building archetype and a pathway to achieving a majority NZEB national stock. Finally, the project contributed positively to human capital in the form of post-doctoral research experience for two employees and the level of knowledge on key areas affecting our goals of achieving a carbon neutral economy.

2.6 Recommendations:

WP3 explores the impact of hygrothermal changes on mould growth following house retrofitting, focusing on the role of accurate environmental input data. The study found discrepancies in the data due to local environmental factors, such as proximity to large bodies of water, suggesting future studies could improve simulation accuracy by calibrating external climatic data and benefit from large scale monitoring campaign across various regions in Ireland. Furthermore, constant shading factors applied due to software constraints could also impact the model's precision, pointing to an area for future refinement in model calibration.

A ventilation rate above 5 ACH was found to mitigate visible mould growth risks, but the assumed ventilation value in the model needs further verification. The results suggest that mechanical ventilation is required in the attic space for dwellings with a dormer structure. Monitoring passive ventilation rates and external local climate conditions for dwellings with varying orientation relative to the wind direction would provide a clearer picture of achievable passive ventilation rates by season throughout Ireland. This could be complimented by computational fluid dynamics modelling and used for calibration with various vent designs and restrictions to the rafter depth. An assessment could then be provided on the need for mechanical ventilation to offset low ventilation through a hybrid natural-mechanical system.

The study confirmed that adding an occupied dormer attic increases mould growth risk but suggested mitigation strategies such as enhanced ventilation through mechanical means and vapour barriers controlled ceiling leakage, thus reducing internal humidity. The inclusion of vapour barrier in the ceiling structure should be a mandated in building regulations for all retrofitted dormer dwellings and minimum 1 ACH for the dormer room in order to lower MGI in both the ceiling and rafter structure. However, more experimental investigations are needed to understand the implications of fluctuating MGI values on different types of buildings and structures. The required attic and dormer room ventilation of 5 ACH and 1 ACH respectively is more than optimal and the use of a vapour barrier, resulting in MGI less than one in the attic space and negligible in the plasterboard ceiling.

WP4 suggests several policy recommendations to improve energy efficiency in residential buildings. Emphasis should be placed on enhancing insulation levels and incorporating heat pumps in dwellings for optimal national energy savings, aiming for A-rated dwellings. Therefore, policy measures should focus on increasing the grant subsidy towards heat pump installation costs, especially considering the predominance of dormer dwellings in rural areas and the need for elimination of oil and peat based fuels. Prioritizing deep energy retrofits over shallow, is also encouraged due to their cost-effectiveness and improved return on investment over a twenty-year life cycle, especially for uninsulated dwellings. The provision of low-interest loans by government entities is a recommend policy change in addition to grant provisions currently on offer by the state to ensure the long-term economic viability of retrofit projects and offset potential market shocks to material costs and volatile fuel prices. An analogous policy measure has been enacted by local authority providing low intertest mortgage (local authority home loan scheme) for first time buyers. Policymakers should also acknowledge the significance of the quantity of retrofits and proportion of heat pumps installed in achieving considerable accumulative energy and life cycle cost savings, and not only focus on insulation upgrades. Lastly, policies should motivate the inclusion of heat pumps in retrofit packages, despite higher initial costs, due to their greater energy savings and life cycle cost benefits for both non-dormer and dormer dwellings, ensuring a more holistic transition away from fossil fuel based heating systems.

2.7 Conclusions and Next Steps:

WP3 analysed the hygrothermal conditions in a semi-detached house, comparing a non-dormer structure with a dormer-style attic room after energy retrofitting. The focus was on the rafter conditions and mould growth index values under different design strategies. The findings showed that an occupied dormer increased the risk of mould growth on the rafters, while the non-dormer had minimal mould growth with low passive ventilation. The dormer dwelling exceeded the critical MGI threshold, requiring mechanical ventilation for mitigation, with 5 ACH required in most instances. The study identified a correlation between rising interior moisture levels, mould growth risk, and higher ceiling leakage rates. Adding a 1mm vapor barrier yielded similar MGI values as increasing ventilation rate. Therefore a combined approach where the room the dormer room is adequately ventilated to a minimum of 1 ACH, installation of a vapour barrier and mechanical ventilation all mitigate the risk of mould growth in the attic and living spaces. Long-term simulations indicated a relatively stable MGI state after 5-7 years, depending on attic ventilation. Incorporating a vapor barrier in building renovations was found to be cost-effective. Over thirty years, using a vapor barrier with different air change per hour scenarios resulted in energy savings and cost reduction, with a payback period of 7-14 years, depending on the required ventilation rates. Expenses associated with mechanical ventilation decreased over time and stabilised, but incorporating a vapor barrier expedited stability and yielded lower costs compared to no vapor barrier. Increasing the dormer window area led to higher energy losses, attic humidity, and mould growth risk. Weather conditions within the climate region also influenced MGI values. Building orientation and location played important roles, with higher natural ventilation rates being more significant. Dublin, with lower outdoor humidity, experienced greater reduction in MGI values with increased ventilation rates.

WP4 applied a comprehensive approach, using bottom-up modelling for both dormer and non-dormer dwellings in residential housing stock, alongside a LCC model to examine pre- and post-retrofit energy and cost savings at individual and national housing stock levels. It found that dormer conversions, while resulting in a larger floor area and up to 30 MWh per annum additional primary energy consumption, could still attain cost-optimal models when retrofitted to an A- or B-rated standard. Uninsulated dwellings demonstrated shorter payback periods (10-12 years) and better returns on investment compared to partially insulated dwellings with payback periods of 17-20 years. However, the cost-optimal retrofit was found to be susceptible to negative returns on investment due to factors like high discount rates, rising capital and heating oil costs, and decreasing electricity costs. Government-backed low-interest loans, along with grants, could support economically viable retrofit projects in the long term. Lastly, on a national scale, the number of retrofits and the inclusion of heat pumps in the retrofit measures greatly influence energy and LCC savings, potentially leading to 13.08 TWh of energy savings by 2030 and total LCC savings of €16.74 billion after twenty years.

Future research:

Future research can focus on the study of the actual efficiency of attic ventilation. This could involve on-site measurements in existing residential attics pre and post retrofit, with long-term monitoring of ACH and roof vent velocities in the attic. A three year study incorporating a large body of housing structures and different building archetypes would be required to provide a better calibrated model and expand knowledge on the building science sector. The results could then be compared with CFD simulation results. Once the CFD model is calibrated, it could be used to predict the passive ventilation efficiency of the attic void, thereby further investigating it's mould growth risk. The CFD model data can be used to ascertain inputs for the hygrothermal models relevant to Irelands ambient and indoor conditions. Moreover, long-term detection of indoor material mould conditions and moulding experiments on materials can provide clearer insights on material performance. In terms of energy and capital savings, research could be extended to include data collection in the form of survey questionnaires and also the expansion of air permeability tests as part of BER assessments. There is a dearth of knowledge and data on the leakage rates for both non-dormer and dormer dwellings in Ireland. This would provide a more accurate understanding of energy usage and cost expenditures in Irish residential buildings. Additionally, the verification of the model presented in this study could be carried out by measuring the actual energy consumption of real projects both before and after retrofitting over a long period of time. This would not only validate the model but also provide practical insights into the effectiveness of different retrofitting measures in reducing energy consumption. This real-world data could then be used to further refine the model and improve its predictive accuracy. A large-scale pilot study of pre and post retrofits would create a clearer picture on the costs involved and produce better economic assessments using LCC methods to entice more homeowners to enact deep energy retrofits.

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