Hulathdoowage, N. D., Karunasena, G., Udawatta, N., Harrington, P. and Liu, C., 2026. Conceptualising an inclusive compliance approach to sustain the energy efficiency of new residential buildings. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 445-458. DOI: https://doi.org/10.31705/WCS.2026.33. Available from: https://ciobwcs.com/papers/

CONCEPTUALISING AN INCLUSIVE COMPLIANCE APPROACH TO SUSTAIN ENERGY EFFICIENCY OF NEW SINGLE-FAMILY HOMES

Nimasha Dilukshi Hulathdoowage[1], Gayani Karunasena[2], Nilupa Udawatta[3], Philip Harrington[4] and Chunlu Liu[5]

ABSTRACT

Just as a roadworthy certificate for a motor vehicle relies on periodic inspections to verify continued safety, residential buildings should also be subject to scheduled compliance checks to ensure they continue to perform safely, efficiently, and sustainably over time. Moving from foresight to action, this study conceptualises an inclusive compliance approach to sustain the energy efficiency of new single-family homes through regular inspection cycles. Developed through a scoping review and desk study, the concept proposes: (i) a practical workflow and supporting equations to determine when new residential buildings should enter their first compliance cycle, and (ii) a method for defining a minimum penalty-free retrofit window to support timely, proactive upgrades, within the initial cycle. The study lays the groundwork for a forward-looking policy framework that strengthens inclusive compliance pathways, promotes early intervention, and advances the transition toward a resilient, energy-efficient, and regenerative housing sector.

Keywords: *Compliance Cycles; Energy Efficiency; Staged Retrofitting; Staged Renovation; Stepwise Retrofitting.*

1. INTRODUCTION

Many dwellings were built before the introduction of minimum energy performance standards, resulting in low baseline efficiency (Birchall et al., 2016). At the same time, millions of new homes are expected to be constructed in the coming decades (Grandolini et al., 2016). Although new homes may comply with energy standards at the point of construction, initial compliance does not ensure sustained performance over the building life cycle. Residential energy performance can drift over time due to climate change, changing occupancy patterns, degradation of building envelope thermal properties,

[1] Postgraduate Researcher, School of Architecture and Built Environment, Deakin University, Australia, n.hulathdoowage@research.deakin.edu.au
[2] Senior Lecturer, School of Architecture and Built Environment, Deakin University, Australia, gayani.karunasena@deakin.edu.au
[3] Senior Lecturer, School of Architecture and Built Environment, Deakin University, Australia, nilupa.udawatta@deakin.edu.au
[4] Technical Advisor, Strategy. Policy. Research., Australia, philip@strategypolicyresearch.com.au
[5] Professor, School of Architecture and Built Environment, Deakin University, Australia, chunlu.liu@deakin.edu.au

Heating, ventilation, and air conditioning (HVAC) system wear, and reduced airtightness (Anh & Pásztory, 2021; Lee et al., 2022; Metehan et al., 2025). Therefore, sustaining the energy efficiency of new homes requires a shift from one-time construction-stage compliance towards periodic reassessment and timely intervention.

Existing policy instruments provide useful foundations but remain limited for this purpose. A notable example is the District of Columbia's Building Energy Performance Standards, which introduced 5–6-year compliance cycles for existing commercial and multifamily buildings (The District of Columbia Department of Energy & Environment, 2023). However, these cycle lengths reflect the governance, finance, and capital-improvement cycles of larger buildings and are not designed to account for the affordability constraints, retrofit scope, access to finance, or local delivery capacity of single-family households (Maia et al., 2021; Calama-González et al., 2025). As a result, such approaches offer limited guidance for designing inclusive compliance mechanisms for new single-family homes.

In Europe, renovation passports have advanced the concept of staged retrofitting by organising building upgrades across multiple steps over an agreed timeline (European Union, 2018). However, the European renovation passport is not currently mandatory and lacks guidance on sustaining the performance of newly built homes (European Commission, 2025). Current instruments, therefore, provide limited support for designing an inclusive compliance approach to sustain the energy efficiency of new single-family homes.

Nevertheless, staged retrofitting provides a useful basis for rethinking residential compliance because it recognises that energy upgrades are not only technical interventions but also time- and budget-dependent household decisions (Maia et al., 2021). This is particularly important for single-family homes, where immediate corrective action after non-compliance may be financially unrealistic. However, existing staged retrofit approaches are primarily designed to improve the performance of existing buildings, rather than to support ongoing compliance in newly built homes (Maia et al., 2021; Calama-González et al., 2025). This creates a gap in the linkage between staged retrofit logic and periodic energy performance reassessment.

Accordingly, this study aims to conceptualise an inclusive compliance approach based on staged retrofitting, thereby contributing to the development of innovative and inclusive residential energy policy.

2. SINGLE-STEP VS STAGED RETROFITTING

Energy retrofitting can be implemented either as a single-step intervention, in which all selected measures are completed at once, or as a staged process, in which measures are sequentially implemented over time. While single-step retrofitting may deliver faster performance improvements, it often requires substantial upfront investment and may be difficult for households with limited financial capacity (Maia et al., 2024). Staged retrofitting, by contrast, allows retrofit measures to be implemented progressively as budgets accumulate, making it particularly relevant for policy approaches that seek to balance energy performance requirements with household affordability. Staged retrofitting, therefore, involves four elements: (i) retrofit start year, (ii) timing between steps, (iii) measures included in each step, and (iv) sequence of steps (Hulathdoowage et al., 2026; Maia et al., 2021). Common energy retrofit measures include insulating the building envelope, replacing windows, installing efficient HVAC, lighting and hot-water systems, and integrating green roofs and walls and domestic PV (Madushika et al., 2023). These measures enhance energy efficiency and climate resilience, reduce emissions, and promote regenerative outcomes in the built environment.

3. RESEARCH METHODOLOGY

The research methodology comprises two phases. First, a scoping review was conducted to identify dynamic parameters that may contribute to post-construction drift in residential energy performance and to inform the timing of the first compliance cycle. The scoping review linked existing evidence on residential performance drift to the simulation-based compliance structure, ensuring transparent, literature-informed parameter selection and decision-stage formulation (Munn et al., 2022). Parameters were selected based on their documented influence on residential energy performance over time, relevance to conditioned single-family homes, suitability as time-varying inputs in building performance simulation, and support from recent peer-reviewed literature. The retained parameters were then coded through content analysis according to the compliance decision stage they informed: benchmark definition, performance simulation, deviation measurement, smoothing of abnormal years, and breach identification. These categories informed the structure of Model 1.

Second, a desk study examined existing staged-retrofitting optimisation models to identify common variables, constraints, and modelling approaches relevant to defining a penalty-free retrofit window. Models were selected based on their focus on staged retrofit optimisation, their application to residential buildings, the transparency of their development, publication quality, and recency. The selected studies were coded according to retrofit costs, household affordability, energy savings, maintenance, residual-value treatment, and optimisation technique. These coded elements informed Model 2. A hierarchical multi-objective optimisation structure was adopted for two reasons: (1) the policy and household objectives are related yet distinct, and (2) Model 2 involves discrete decisions regarding the selection and timing of retrofit measures within a linear optimisation framework (Halffmann et al., 2022). This hierarchy prioritises the minimum penalty-free retrofit window before optimising household cash flow.

As this study proposes a conceptual decision-support framework, the models are not empirically calibrated at this stage. Rather, the study establishes a transparent, literature-informed set of equations and model structure as a necessary foundation for subsequent expert refinement and case-study testing within the broader research programme.

4. THE PROPOSED COMPLIANCE APPROACH FOR NEW SINGLE-FAMILY HOMES

This section conceptualises a method for developing an inclusive compliance approach. This includes designing two linked models: (i) model 1: determining the timing of the first compliance cycle for new single-family homes to provide advance notice of the first checkpoint, and (ii) model 2: defining a penalty-free retrofit window to allow retrofitting for houses whose performance deviates from the initial benchmarks before imposing any penalty. The workflows of these two models are presented in Figure 1.

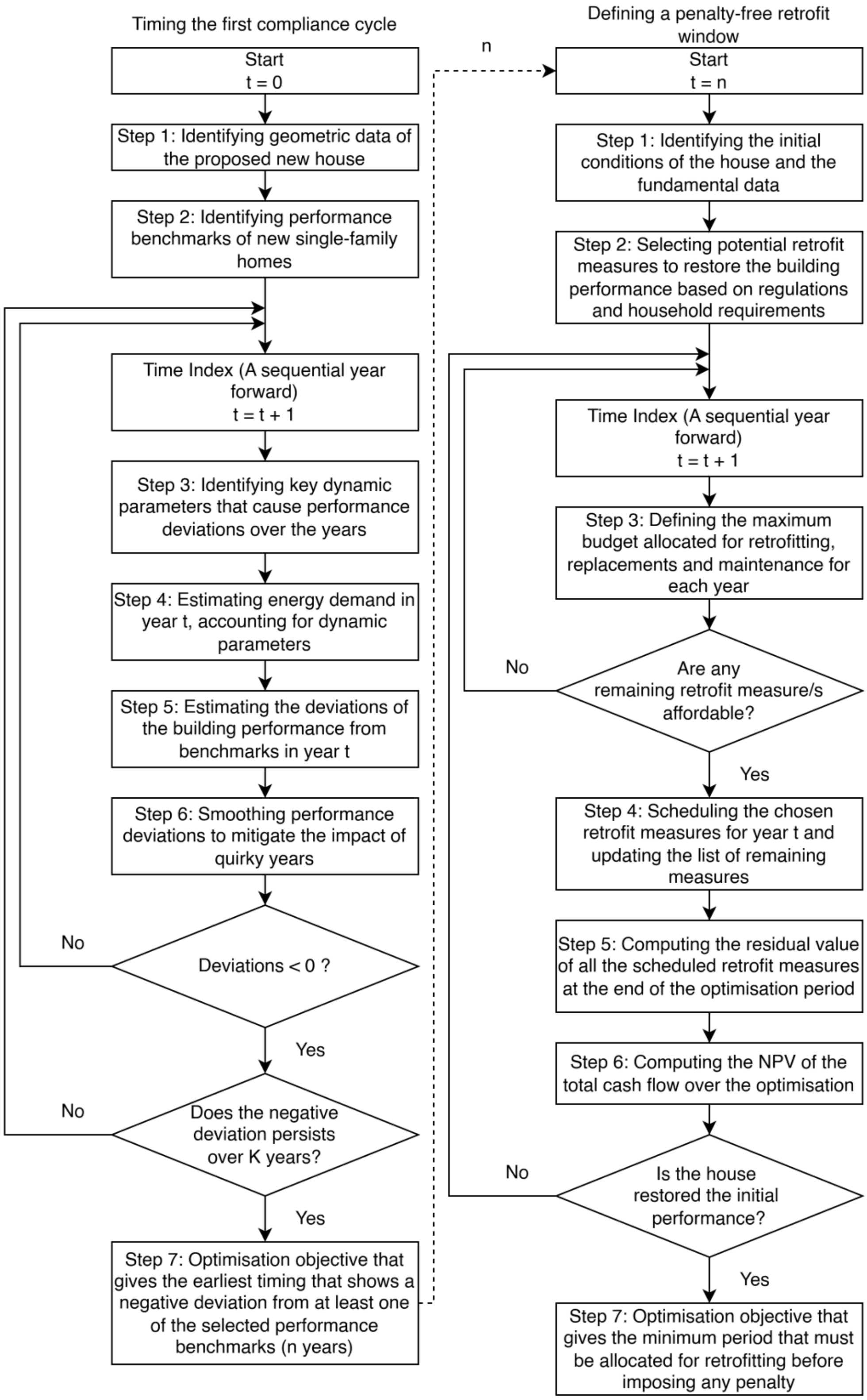

Figure 1: The workflows of the two proposed models

Notes: t - any year within the optimisation period, K - the number of years used to check the persistence of the breach, n - the earliest year when the building's performance deviates from a benchmark, NPV – Net Present Value; The output of model 1 is an input to model 2.

4.1 MODEL 1: TIMING THE FIRST COMPLIANCE CYCLE

Multiple dynamic factors can drive performance drift in residential buildings, including climate change and evolving occupancy patterns, material degradation that alters envelope thermal properties and HVAC efficiency, and broader system shifts such as changes in the electricity mix that modify emissions outcomes for the same energy use (Eleftheriadis & Hamdy, 2018; Anh & Pásztory, 2021; Metehan et al., 2025; Taki & Zakharanka, 2023). For example, Taki and Zakharanka (2023) found that ageing can substantially increase cooling demand, with projected rises of 9.53%–38.40% over 25 years in UAE housing. Pajek et al. (2023) proposed a multi-objective retrofit framework, showing that optimal retrofit packages could reduce energy demand by 75%, 66%, and 59% under current and future climates (RCP4.5 and RCP8.5). Together, these studies underscore that performance drift is multi-causal. Yet, much of the literature still evaluates the performance deterioration in new homes through a single dynamic factor, most often climate change, rather than accounting for multiple interacting drivers. This leaves no defensible basis for determining when the first compliance cycle should begin to evaluate the performance of new single-family homes. Hence, Figure 1 presents a novel model workflow for timing the first compliance cycle of new homes, and the subsequent section describes its key components. This workflow accommodates jurisdiction-specific benchmarks and varying sets of dynamic parameters, depending on the regulatory context, climate conditions, and the scope of the energy performance assessment.

- Step 1: Identifying the geometric data of the proposed new house

A building simulation, a computer model that predicts how a house will perform (Beausoleil-Morrison, 2020), requires geometric data that defines the structure's 3D form and the boundaries of its spaces, including the volumes of rooms or thermal zones, boundary surfaces such as walls, roofs, and floors, along with their areas, orientations, and vertices, and the placement and dimensions of openings like windows and doors. It also needs adjacency and boundary classifications, basic orientation, site context, and any shading geometry that influences sun and wind exposure.

- Step 2: Identifying performance benchmarks of new single-family homes

Any voluntary/ mandatory benchmarks applicable to new house construction in the selected country/ region should be identified. These benchmarks can also be expressed as functions of time. For example, the equations introduced by the Australian government for 7-star benchmarks for new residential buildings include parameters associated with outdoor temperature and humidity. While these parameters are currently derived from historical climate data, the equations could also accommodate climate change as occupants adjust their comfort settings over time. Still, the static benchmarks can also be integrated into the model. The number and type of benchmarks depend on the selected country or region. For example, Australia uses three thermal energy benchmarks: heating, cooling, and total thermal energy demand.

- Step 3: Identifying key dynamic parameters that cause deviations in energy efficiency over time

According to the scoping review, four key dynamic parameters that cause deviations in thermal energy efficiency over time were identified, including (i) climate variations (Chen et al., 2021), (ii) thermal conductivity of insulation (Anh & Pásztory, 2021), (iii) Coefficient of Performance (COP) of heat pumps (Eleftheriadis & Hamdy, 2018), and

(iv) airtightness (Moujalled et al., 2021). These parameters are applicable to conditioned single-family homes globally. However, when evaluating the whole-building energy efficiency, the efficiency of other appliances, such as stoves and solar hot water systems, should also be considered. Thus, the number of dynamic parameters depends on the scope of the energy performance assessment.

- Step 4: Estimating energy demand each year, accounting for dynamic parameters

Annual energy demand is estimated using building simulation, updating the model inputs based on relevant dynamic parameters while holding time-invariant attributes (e.g., geometry, zoning, and fixed construction properties) constant. Accordingly, the annual simulations use a climate representation for each year (e.g., an actual or scenario-based weather file) and incorporate the evolution of relevant dynamic parameters, extracted from contemporary experimental studies. Simulation outputs are reported as annual metrics, including cooling demand, heating demand, total thermal demand, whole-house energy demand, and renewable energy generation, with the selected output categories depending on the performance benchmarks. Where dynamic parameters are uncertain, simulations are repeated across defined ranges or distributions to quantify sensitivity and avoid over-interpreting minor differences.

- Step 5: Estimating performance deviations from benchmarks in each year

The performance deviation from each benchmark is calculated annually as the difference between the buffered benchmark and the measured energy performance (see Equation 01) to understand whether the building still complies with the benchmark. A buffer (i.e., a tolerance margin) is intentionally applied to the benchmark to account for normal, non-actionable variation, so that minor exceedances are not automatically interpreted as genuine underperformance. For example, a 5% buffer is appropriate in the Australian residential context because Nationwide House Energy Rating Scheme (NatHERS) itself treats ±5% as an "acceptable difference" when accrediting software for energy rating: at least 95% of simulations must align with the benchmark within ±5% (or ±5 MJ/m²·annum) for both heating and cooling loads (Nationwide House Energy Rating Scheme, 2024).

$$PD_i(t) = (1 + \delta) \times PB_i(t) - BP(t) \quad \forall i \in [1, 2, 3, \dots, x] \qquad (01)$$

where, $PD_i(t)$ = performance deviation from a selected performance benchmark in year t, $PB_i(t)$ = the selected performance benchmark in year t, δ = buffer margin for the deviation, BP(t) = the building performance in year t, and x = the number of prevailing performance benchmarks for new home construction

- Step 6: Smoothing performance deviations to mitigate the impact of anomalous years

Annual performance deviations, calculated using Equation 01, are smoothed to prevent false alarms of building performance deviations caused by anomalous years. Annual deviations can vary non-monotonically due to climate variability and nonlinear material degradation, so raw values may show a breach in 2031, a return to compliance in 2032, and a breach again in 2033, making the "earliest breach year" unstable and misleading. Thus, Equation 02 smooths performance deviations over ω years, while Equation 03 smooths over three years, offering a simplified version of Equation 02. The selected smoothing period (ω) should be an odd number to provide a symmetric, centred window around the current year, ensuring an equal number of years on either side and avoiding bias towards earlier or later years when estimating the smoothed deviation.

$$\overline{PD}_i(t) = \frac{1}{\omega} \sum_{j \in J} PD_i(t + j) \quad \forall J \in [-h, (-h + 1), \ldots, (h - 1), h] \qquad (02)$$

where, $\overline{PD}_i(t)$ = smoothed performance deviation from a selected performance benchmark in year t, ω = smoothing period, $PD_i(t + j)$ = performance deviation from a selected performance benchmark in any year within the smoothing period, h = $\frac{(\omega-1)}{2}$, where $\omega \equiv 1$, j = any year within the smoothing period, and J = all the years within the smoothing period

$$\overline{PD}_i(t) = [PD_i(t - 1) + PD_i(t) + PD_i(t + 1)]/3 \qquad (03)$$

where, $\overline{PD}_i(t)$ = smoothed performance deviation from a selected performance benchmark in year t, and $PD_i(t - 1)$, $PD_i(t)$, and $PD_i(t + 1)$ = performance deviation from a selected performance benchmark in year (t - 1), t, and (t + 1)

- Step 7: Optimisation objective

Model 1 aims to identify the earliest year of a breach by simulating how key dynamic factors influence building performance over time. Equation 04 sets out the compliance rule for the selected performance benchmarks within a given country or region. The breach year is defined as the first year in which building energy performance exceeds at least one benchmark and then remains above that benchmark for K consecutive years. This breach year marks the start of the first compliance cycle.

$$\tau = min\{t: [(\overline{PD}_1 \leq 0) \vee (\overline{PD}_2 \leq 0) \vee (\overline{PD}_3 \leq 0) \ldots \vee (\overline{PD}_x \leq 0)] \; for\ K\ consecutive\ years\} \qquad (04)$$

where, $\overline{PD}[1](t)$ = smoothed deviation from the first benchmark, and x = the number of benchmarks, and K = the number of years used to check the persistence of the breach

4.2 MODEL 2: DEFINING A PENALTY-FREE RETROFIT WINDOW FOR THE FIRST COMPLIANCE CYCLE

Five optimisation models were selected for the desk-study case comparison. These models focused on minimising energy-related expenses in social housing and maximising cash flows for owner-occupied single-family homes across various European settings (De Moortel et al., 2018; Maia et al., 2021, 2023, 2024; Nicoletti et al., 2025). Collectively, these studies focus on existing dwellings. They suggest that staged retrofitting can outperform single-step upgrades because household budgets accumulate over time, enabling deeper measures (Maia et al., 2021; Maia et al., 2024). Reported retrofit cycles range from 1–14 years, depending on replacement effects (Maia et al., 2021), and around 12 years when constrained by household income (Maia et al., 2024). However, these studies do not optimise the total retrofit duration to achieve a targeted performance level; instead, they optimise the spacing between retrofit steps to implement a pre-selected list of retrofit measures. In contrast, this study optimises the full duration required to restore the house to its original performance. This optimal duration defines a minimum retrofit window that must be allocated before any penalty is imposed. Unlike prior models, which are largely household-centred, this study incorporates both household and policymaker perspectives when modelling staged retrofitting to inform an inclusive policy framework.

The desk study identified common parameters used in staged retrofitting models (see Table 1). These parameters indicate that economic factors and budget constraints underpin staged retrofitting (De Moortel et al., 2018; Maia et al., 2021, 2023, 2024; Nicoletti et al., 2025). Using those parameters, the model workflow was developed for defining an optimal penalty-free retrofit window for the first compliance cycle of a new single-family home (see Figure 1). The following sections outline its main components.

Table 1: Characteristics of existing staged retrofitting models

Studies/ Models	[1]	[2]	[3]	[4]	[5]
Parameters/ Variables/ Constraints					
Initial investment cost of retrofit measures	✓	✓	✓	✓	✓
Energy savings of retrofit measures		✓	✓	✓	✓
Combinations of retrofit measures		✓	✓	✓	
Maintenance cost		✓	✓	✓	✓
Insurance cost					✓
Bank loan availability					✓
Bank loan repayment duration					✓
Bank loan interest rate					✓
Annual electricity and gas costs	✓	✓	✓	✓	✓
Inflation in general					✓
Inflation of electricity and gas prices	✓	✓	✓	✓	✓
Discount rate	✓	✓	✓	✓	✓
Material ageing		✓	✓	✓	
Building life span	✓				✓
Thermal resistance	✓				
Lower calorific value	✓				
Equivalent degree days	✓				
Efficiency of the heating system	✓				
The maximum budget allocated for retrofitting		✓	✓	✓	✓
The maximum debt pressure					✓
Energy bill savings must cover the outstanding loan before the next retrofit step					✓
Dependency of replacements		✓	✓	✓	
Optimisation Techniques					
MILP to formulate the optimisation problem		✓	✓	✓	✓
Brute-force algorithm to evaluate possible combinations					✓
Gurobi solver to evaluate possible combinations		✓	✓	✓	
Excel-based analysis of the Pareto front for LCC	✓				

[1] - De Moortel et al. (2018), [2] - Maia et al. (2021), [3] - Maia et al. (2023), [4] - Maia et al. (2024), [5] Nicoletti et al. (2025)

- Step 1: Identifying the initial conditions of the house and the fundamental data

Step 1 establishes the baseline for Model 2 by anchoring it to the breach year identified in Model 1. The associated benchmark and building energy performance define the initial performance gap and the onset of the first compliance cycle. The required economic data are then used to represent budget accumulation and to value retrofit costs and energy savings over time. These data include household income, income growth, energy prices, energy price inflation, general inflation, and the chosen discount rate for Net Present Value (NPV) calculations.

- Step 2: Selecting potential retrofit measures to restore the building performance based on regulations and household requirements

Step 2 compiles a feasible set of retrofit measures that could close the identified performance gap and return the dwelling to the required benchmark. Measures are first screened against applicable regulations and compliance requirements. These measures are then filtered for household suitability, considering practical constraints such as affordability, disruption, technical compatibility with the dwelling, and occupant needs. Clearly defining this measure set is critical because it bounds the optimisation to realistic, compliant options and ensures the resulting staged pathway reflects what can actually be delivered in practice, rather than an idealised solution. Accordingly, the resulting shortlist forms the candidate measure set for the staged retrofit optimisation.

- Step 3: Defining the maximum budget allocated for retrofitting in each year

A defined proportion of annual household income is allocated to the retrofit budget, which is used for retrofit measures and the maintenance of installed measures. A rationalised income allocation can be defined at the country or regional level as twice the median proportion of the household energy expenditure (Boardman, 1991; Nicoletti et al., 2025). The same approach can also be applied at the individual household level by using the household's own energy expenditure proportion rather than the regional median. Because the retrofit budget is cumulative, any unspent funds from the previous year are carried forward and added to the budget in year t. Accordingly, Equation 05 defines the maximum retrofit budget available in year t for investment in retrofit measures.

$$RB(t) = RB(t-1) + [IS(t) - EB(t) - MC(t)] \times DF(t) \qquad (05)$$

where, RB(t) = the maximum budget available for retrofitting in year t [$/yr], RB(t – 1) = the remaining funds carried over from the previous year [$/yr], IS(t) = the amount of household income allocated for energy retrofitting in year t [$/yr], EB(t) = total cost of energy bill in year t [MJ/yr], MC(t) = total maintenance cost in year t, and DF(t) = discounting factor for year t

The real discounting factor for each year is defined in Equation 06, accounting for the evolution of the interest rate. This factor is important because it converts future costs and savings into present-value terms, reflecting the time value of money and enabling consistent comparison of retrofit investments and benefits that occur in different years.

$$DF(t) = 1/[\prod_{i=1}^{n+t} (1 + r_i)] \qquad (06)$$

where, DF(t) = discounting factor for year t, r_i = interest rate in discounting year i, and n = breach year

Equation 07 derives household income in the current year from the previous year's income using the annual income growth rate. Then, the amount allocated to energy retrofitting is calculated by applying the retrofit-income proportion.

$$IS(t) = INC(t-1)[1+g(t)] \times f \qquad (07)$$

where, IS(t) = the amount of household income allocated for energy retrofitting in year t [$/yr], INC(t – 1) = annual household income in the previous year [$/yr], g = annual household income growth in year t, f = the retrofit-income proportion [%]

Equation 08 estimates the household's total energy bill for the current year by summing the costs of each energy source, where each cost is calculated as the product of the energy quantity and its unit price. Forecasted annual unit prices are used when available; otherwise, initial prices can be used and updated using the energy inflation rate.

$$EB(t) = \sum_{es}[\, ED_{es}(t) \times pr_{es}(t)\,] \qquad (08)$$

where, EB(t) = total cost of energy bills in year t [$/yr], es = energy sources, $ED_{es}(t)$ = total energy demand of the energy source 'es' in year t [kWh/yr], and $pr_{es}(t)$ = energy unit price of the energy source 'es' in year t [$/kWh]

Equation 09 calculates the annual energy demand for each energy source in the current year. This demand is estimated by deducting the anticipated energy savings from retrofit measures installed in the previous year from the previous year's demand. The energy savings from each measure are assumed to be realised from the year after implementation and to continue in subsequent years.

$$ED(t) = ED(t-1) + \sum_{m=0}^{M} ES_m \qquad (09)$$

where, ED(t) = total energy demand in year t [kWh/yr], ED(t – 1) = total energy demand in the previous year [kWh/yr], ES_m = energy savings of each retrofit measure [kWh/yr], and M = all the retrofit measures scheduled for the previous year

Equation 10 computes the annual maintenance costs associated with scheduled retrofit measures. The maintenance cost of each measure is assumed to be realised from the year after implementation and to continue in subsequent years. Maintenance is included because proper upkeep helps moderate the effects of natural ageing and mechanical wear of HVAC systems. In contrast, poor maintenance can lead to a near doubling of energy consumption over the long term (Eleftheriadis & Hamdy, 2018).

$$MC(t) = \sum_{m=0}^{MM} MC_m \qquad (10)$$

where, MC(t) = total maintenance cost in year t [$/yr], MC_m = annual maintenance cost of each retrofit measure [$/yr], MM = all the retrofit measures scheduled before year t

Step 4: Scheduling the chosen retrofit measures for year t and updating the list of remaining measures

If the initial investment cost of an available retrofit measure falls within the budget defined in Equation 05, the measure is eligible for scheduling in the current year. Equation 11 computes the total initial investment cost of the measures scheduled for the current year. Next, the list of remaining retrofit measures is updated.

$$RC(t) = \sum_{m=0}^{y}[MaterialC_m(t) + LabourC_m(t)] \qquad (11)$$

where, RC(t) = total initial investment cost of retrofit measures scheduled for year t [$], $[MaterialC_m(t), LabourC_m(t)$ = material and labour costs of each retrofit measure [$], y = all the retrofit measures scheduled for year t, n = the breach year

Wright's law can be used to estimate price fluctuations in materials for retrofit measures because their cost reductions are associated with broader adoption and cumulative production (Moghaddam et al., 2023). Wright's law states that the cost of a technology tends to decrease by a roughly constant percentage each time its cumulative production doubles, driven by learning-by-doing and technological advancements (Wright, 1936).

- Step 5: Computing the residual value of all the scheduled retrofit measures at the end of the optimisation period

Equation 12 computes the residual value of all retrofit measures scheduled up to the current year by the end of the optimisation period. The residual value is included because many retrofit measures retain useful life and economic value beyond the optimisation period. This is particularly important in staged retrofitting pathways, where retrofit measures are implemented at different time intervals. Crediting this remaining value prevents the undervaluation of late investments, enhances fairness when comparing measures with varying lifetimes, and minimises bias at the end of the optimisation period.

$$L(T) = DF(T) \times \sum_{m=0}^{N} C_m \times \frac{max\,(0,\ TL_m - (T - i_m))}{TL_m} \qquad (12)$$

where, L(T) = discounted residual value of all the retrofit measures scheduled up to the current year by the end of the optimisation period [$/yr], N = the total number of measures scheduled up to the current year, C_m = initial investment cost of each measure [$], i_m = the year each measure is scheduled, TL_m = technical life time of each measure, T = end of the optimisation period, and DF(T) = discounting factor in year T

- Step 6: Computing the NPV of the total cash flow over the optimisation period

Equation 13 computes the NPV by summing the discounted annual cash flows over the optimisation period, including allocated household income, retrofit costs, energy costs and savings, maintenance costs, and residual values of retrofit measures. By converting costs and savings from different years into a consistent present-value basis, the NPV formulation provides the economic basis for evaluating alternative staged-retrofit pathways and their timing across the optimisation period. Thus, this formula underpins the optimisation objective.

$$NPV = \sum_{t=n}^{T} \{[IS(t) - RC(t) - EB(t) - MC(t)] \times DF(t)\} + L(T) \qquad (13)$$

where, NPV = net present value of the total cash flow over the optimisation period, n = the breach year, T = end of the optimisation period, IS(t) = the amount of household income allocated for energy retrofitting in year t [$/yr], RC(t) = total initial investment cost of retrofit measures scheduled for year t [$], EB(t) = total cost of energy bills in year t [MJ/yr], MC(t) = total maintenance cost in year t, DF(t) = discounting factor in year t, L(T) = discounted residual value of all the scheduled retrofit measures up to year t by the end of the optimisation period, r = interest rate, and tp = depreciation time

- Step 7: Optimisation objective that gives the minimum period that must be allocated for retrofitting before imposing any penalty

Model 2 aims to determine the minimum retrofit period to allocate during the initial compliance cycle, prior to the enforcement of penalties, also known as the penalty-free retrofit window. As presented in Equation 14, the model first minimises the retrofitting period as the primary objective. The model then maximises the household's cash flow as the secondary objective, allowing retrofit measures to be scheduled without compromising the minimum retrofitting window. This hierarchical multi-objective approach ensures that the minimum retrofit window is not compromised when maximising the household's cash flow. Retrofit measures will be implemented as the budget is accumulated and until the house regains its initial energy performance. The model adjusts the timing and sequence of scheduled retrofit measures during the optimisation process to achieve the best outcomes for the optimisation objective, given in equation 14.

$$Min\ (T_{\omega}\ at\ priority\ 1), Max\ (NPV\ at\ priority\ 2) \qquad (14)$$

where, T_{ω} = timing to restore the energy performance and NPV = net present value of the total cash flow over the optimisation period

5. CONCLUSIONS AND FUTURE OUTLOOKS

This study conceptualises an inclusive compliance approach to sustaining the energy efficiency of new single-family homes through periodic reassessment, timely intervention, and adaptive and inclusive policy design. It introduces two linked models for: (i) determining the timing of the first compliance cycle by estimating when building performance first exceeds the required benchmark under key dynamic parameters, and (ii) defining a minimum penalty-free retrofit window within that first cycle using staged retrofitting.

The proposed models shift compliance from a one-off approval requirement toward a more adaptive process for sustaining building energy performance over time. In doing so, the study contributes to policy discussions on long-term building performance and practical compliance mechanisms for sustainable housing. The models can be recalibrated across different climatic, regulatory, and socio-economic contexts, allowing policy settings to remain responsive to changing conditions.

Unlike existing staged retrofitting models, which primarily reflect the homeowner perspective, the proposed approach incorporates the roles of both households and policymakers, revealing an underexplored opportunity in staged retrofitting. Given that macroeconomic conditions may shift over time, the retrofit window should be recalibrated before implementation to keep policy settings aligned with prevailing conditions. The models are therefore intended as adaptive decision-support tools that can guide early intervention, support staged upgrades, and help sustain energy efficiency beyond initial compliance.

Further potential lies in automating compliance through utility bills to enable continuous monitoring, early warnings of likely non-compliance, and more proactive retrofit planning. While this study focuses specifically on energy efficiency, future research could examine whether a similar modelling logic may be adapted to other resource-efficiency domains, such as water efficiency, subject to the development of appropriate performance indicators, cost variables, monitoring mechanisms, and regulatory benchmarks.

Overall, the proposed models lay the foundation for an innovative and inclusive policy framework for sustaining energy-efficiency compliance in new single-family homes. By promoting continuous monitoring, timely upgrades, and adaptive performance improvements beyond initial compliance, this framework can support the sustained resilience, energy efficiency, and progressive regeneration of the housing sector. The next step is to refine and validate the proposed workflows and equations with input from an expert focus group. The broader scope involves testing the models through real-world case studies across diverse climatic, regulatory, and socio-economic contexts.

6. ACKNOWLEDGEMENT

The authors used Grammarly for proofreading, then reviewed and edited the content, taking full responsibility for the final article.

7. REFERENCES

Anh, L. D. H., & P´asztory, Z. (2021). An overview of factors influencing thermal conductivity of building insulation materials. *Journal of Building Engineering, 44*, 102604. https://doi.org/10.1016/j.jobe.2021.102604

Beausoleil-Morrison, I. (2020). *Fundamentals of building performance simulation*. Routledge. https://doi.org/10.1201/9781003055273

Birchall, S., Gustafsson, M., Wallis, I., Dipasquale, C., Bellini, A., & Fedrizzi, R. (2016). Survey and simulation of energy use in the European building stock. In P.K. Heiselberg (Ed), *CLIMA 2016 - Proceedings of the 12th REHVA World Congress* (Vol. 1). Aalborg University. https://vbn.aau.dk/ws/portalfiles/portal/233774195/paper_273.pdf

Boardman, B. (1991). *Fuel poverty: From cold homes to affordable warmth*. Belhaven Press.

Calama-González, C. M., Escandón, R., Suárez, R. & Ascione, F., (2025). Decision-making for renovating the Mediterranean social housing: A practical approach through an interactive open access tool. *Energy and Buildings, 336*, 115629. https://doi.org/10.1016/j.enbuild.2025.115629

Chen, S., Ren, Z., Tang, Z., & Zhuo, X. (2021). Long-term prediction of weather for analysis of residential building energy consumption in Australia. *Energies, 14*(16), 4805. https://doi.org/10.3390/en14164805

De Moortel, E. V., De Troyer, F., Allacker, K., Stijnen, L., & Schoofs, E. (2018). Avoiding financial lock-in effects in case of a stepwise energy renovation of social housing in Flanders. *WEENTECH Proceedings in Energy, 4*(2), 160-176. https://www.researchgate.net/publication/330099120_Avoiding_financial_lock-in_effects_in_case_of_a_stepwise_energy_renovation_of_social_housing_in_Flanders

Eleftheriadis, G., & Hamdy, M. (2018). The impact of insulation and HVAC degradation on overall building energy performance: A case study. *Buildings, 8*(2), 23. https://doi.org/10.3390/buildings8020023

European Commission (2025). *Renovation Passports* (Article 12, Annex VIII, EU/2024/1275). https://energy.ec.europa.eu/document/download/0a4a6d59-58c0-4e80-a58a-a6ee944573ab_en?filename=Renovation%20passport%20%28Article%2012%2C%20Annex%20VIII%29%20-%20annex%204.pdf

European Union (2018, May 30). *Directive 2010/31/EU on the energy performance of buildings and directive 2012/27/EU on energy efficiency*. Retrieved January 15, 2026, from https://eur-lex.europa.eu/eli/dir/2018/844/oj/eng

Grandolini, G. M., & Ijjasz-Vasquez, E. (2016, May 25). *3 reasons why 'Housing for All' can happen by 2030*. World Bank Blogs. https://blogs.worldbank.org/en/voices/3-reasons-why-housing-all-can-happen-2030

Halffmann, P., Schäfer, L. E., Dächert, K., Klamroth, K., & Ruzika, S. (2022). Exact algorithms for multi objective linear optimization problems with integer variables: A state of the art survey. *Journal of Multi-Criteria Decision Analysis, 29*(5–6), 341–363. https://doi.org/10.1002/mcda.1780

Hulathdoowage, N. D., Karunasena, G., Udawatta, N., & Liu, C. (2026). The applicability of stepwise retrofitting in the Australian residential sector: An exploratory qualitative study. *Smart and Sustainable Built Environment*. Emerald Insight. https://doi.org/10.1108/SASBE-04-2025-0180

Lee, J. H., Kim, D. G., Jeong, S. K., & Song, Y. H. (2022). Analysis of heat source system degradation due to aging and evaluation of its effect on energy consumption. *Energies, 15*(23), 9217. https://doi.org/10.3390/en15239217

Madushika, U. G. D., Ramachandra, T., Karunasena, G., & Udakara, P. A. D. S. (2023). Energy Retrofitting Technologies of Buildings: A Review-Based Assessment. *Energies, 16*(13), 4924. https://doi.org/10.3390/en16134924

Maia, I., Kranzl, L., & Müller, A. (2021). New step-by-step retrofitting model for delivering optimum timing. *Applied Energy, 290,* 116714. https://doi.org/10.1016/j.apenergy.2021.116714

Maia, I.E.N., Harringer, D., & Kranzl, L. (2023). Staged renovation and the time perspective: Which other metric should be used to assess climate-optimality of renovation activities?, *Smart Energy, 11*, 100110. https://doi.org/10.1016/j.segy.2023.100110

Maia, I.E.N., Harringer, D., & Kranzl, L. (2024). Household budget restrictions as reason for staged retrofits: A case study in Spain. *Energy Policy, 188, 114047*. https://doi.org/10.1016/j.enpol.2024.114047

Metehan, A. A., Solmaz, A. S., Gök, O., & Tokuç, A. (2025). Adapting to climate change: Assessing future residential energy demands for different climate and occupancy scenarios in Turkey. *Buildings, 15*(8), 1255. https://doi.org/10.3390/buildings15081255

Moghaddam, S.A., Serra, C., da Silva, M.G., & Simões, N. (2023). Comprehensive review and analysis of glazing systems towards nearly zero-energy buildings: Energy performance, thermal comfort, cost-effectiveness, and environmental impact perspectives. *Energies, 16*(17), 6283. https://doi.org/10.3390/en16176283

Moujalled, B., Leprince, V., Berthault, S., Litvak, A., & Hurel, N. (2021). Mid-term and long-term changes in building airtightness: A field study on low-energy houses. *Energy and Buildings, 250,* 111257. https://doi.org/10.1016/j.enbuild.2021.111257

Munn, Z., Pollock, D., Khalil, H., Alexander, L., McInerney, P., Godfrey, C. M., Peters, M., & Tricco, A. C. (2022). What are scoping reviews? Providing a formal definition of scoping reviews as a type of evidence synthesis. *JBI Evidence Synthesis, 20*(4), 950–952. https://doi.org/10.11124/JBIES-21-00483

Nationwide House Energy Rating Scheme. (2024). *Software accreditation protocol – New homes 2025* (Version 20241122). https://www.nathers.gov.au/sites/default/files/2025-11/SAP%20New%20Homes%202025%2020241122.pdf

Nicoletti, F., Carpino, C., Barbosa, G., Domenico, A., Arcuri, N., & Almeida, M. (2025). Building renovation passport: A new methodology for scheduling and addressing financial challenges for low-income households. *Energy and Buildings, 331*, 115353. https://doi.org/10.1016/j.enbuild.2025.115353

Pajek, L., Jevrić, M., Ćipranić, I., & Košir, M. (2023). A multi-aspect approach to energy retrofitting under global warming: A case of a multi-apartment building in Montenegro. *Journal of Building Engineering, 63*, 105462. https://doi.org/10.1016/j.jobe.2022.105462

Taki, A., & Zakharova, A. (2023). The impact of degradation on a building's energy performance in hot-humid climates. *Buildings, 15*(2), 1145. https://doi.org/10.3390/su15021145

The District of Columbia Department of Energy & Environment. (2023). *Building energy performance standards compliance and enforcement guidebook for compliance cycle 1* (Version 1.1). https://dc.beam-portal.org/helpdesk/kb/BEPS_Guidebook/78/

Wright, T.P. (1936). Factors affecting the cost of airplanes. *Journal of the Aeronautical Sciences*, 3(4), 122–128. https://doi.org/10.2514/8.155