



Article

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Abstract

Sustainable renovation of existing residential building stocks is essential to reduce greenhouse gas emissions, improve energy performance, and support long-term climate-neutral housing strategies. However, decisions based only on operational indicators may overlook important product-stage embodied impacts, especially in highly integrated renovation solutions. This study evaluates how alternative renovation pathways for a public residential building portfolio in the Comunitat Valenciana (Spain) perform from a stock-level sustainability perspective, comparing five INFINITE industrialised retrofit kits (Kit 1–Kit 5) with five paired conventional renovation scenarios (S1–S5). A bottom-up building stock modelling workflow is applied, combining building-energy simulation to quantify operational performance and emissions (B6) with a screening life-cycle assessment of product-stage embodied carbon reported as GWP (A1–A3). To relate upfront and in-use impacts, the study computes carbon payback, cumulative emissions avoided, and a horizon-based partial life-cycle climate indicator, PLC(H), assessed for 2030, 2035, and 2050. The results show a clear sustainability trade-off: renovation packages that sharply reduce operational emissions often require higher upfront embodied carbon, shifting net climate benefits towards longer time horizons. Low-embodied options provide earlier benefits, with Kit 1 reducing PLC(H) by 15.5% by 2030, whereas deeper decarbonisation packages achieve stronger long-term outcomes, with S5 reducing PLC(H) by 70.7% by 2050. A bounded electricity-decarbonisation sensitivity further shows that these long-horizon rankings are affected by lower grid-emission factors, particularly for highly electrified pathways, although the strongest 2050 pathways remain robust across the tested cases. Overall, the findings show that sustainable stock-level renovation planning should jointly consider operational and embodied carbon, carbon payback, and milestone-based cumulative impacts in order to support balanced portfolio sequencing between broadly deployable fast-payback measures and selective deep retrofits.

Keywords: sustainable renovation; public housing; building stock modelling; industrialised retrofit; embodied carbon; operational carbon; carbon payback



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1. Introduction

Carbon neutrality has become a widely adopted objective worldwide as a response to climate change, rising energy demand, and growing concern over the long-term envi-

ronmental impacts of the built environment. In the European Union, the building sector is a key leverage point: buildings account for around 40% of final energy consumption and 36% of energy-related greenhouse gas emissions, and a large share of the stock remains energy-inefficient [1]. Reducing energy demand and increasing the contribution of renewable energy—particularly solar energy—are also central to reducing dependence on fossil fuels and imported energy carriers, consistent with wider EU energy-security objectives [1].

Beyond operational energy, buildings represent a long-term “material bank”, and design choices related to construction systems and materials influence greenhouse gas emissions across the life cycle. Accordingly, policy and research increasingly emphasise the need to consider not only operational emissions but also life-cycle contributions, particularly as renovation activity scales up [1]. The Energy Performance of Buildings Directive (EPBD) recast sets a trajectory towards zero-emission new buildings and introduces stock-level targets for the residential sector based on reductions in average primary energy use by 2030 and 2035 [2]. This underscores the importance of addressing the operational-embodied trade-off in renovation, ensuring operational savings are not offset by higher upfront emissions.

At the same time, the challenge is substantial: a large fraction of today’s residential buildings will remain in use by 2050, and many require energy renovation [3]. For this reason, recent research increasingly treats renovation as a stock-level sustainability challenge rather than a sequence of isolated building upgrades. Simulation-based approaches and stock modelling have become central to assessing renovation pathways, quantifying energy impacts and exploring scenario-based strategies [4–7]. At regional and national scales, recent work has demonstrated the value of archetype-based modelling to estimate energy savings and operational CO₂ reductions and to support strategic planning [4,8,9]. For instance, Serrano-Lanzarote et al. identify pre-regulation residential segments as priorities for large-scale renovation in the Comunitat Valenciana and quantify the potential for operational savings [8], while other approaches emphasise the need for robust data and modelling to monitor decarbonisation progress and inform national renovation strategies [9].

However, the sustainability challenge is not only technical. Analyses of mass-renovation strategies indicate that large-scale deployment remains weakly operationalised in many contexts, and that practical implementation depends on factors such as stable demand, supply-chain coordination, and the wider adoption of off-site and prefabricated approaches. In this respect, industrialised and prefabricated renovation has been proposed as a pathway to accelerate deep retrofits at scale. Industrialisation is often framed as a potential “game-changer” for renovation programmes because it can standardise processes and reduce on-site disruption, enabling faster deployment of envelope and system upgrades [10]. This is particularly relevant for public-housing portfolios, where renovation needs intersect with constraints on disruption, procurement and implementation capacity [11]. However, industrialised solutions may increase the quantity and integration of components compared to conventional on-site measures, raising questions about how operational benefits compare with upfront embodied impacts and how preferred options may change with the decision horizon. From a sustainability perspective, public-housing renovation therefore requires not only technically effective measures, but also balanced and scalable pathways that can reconcile near-term action with long-term decarbonisation goals.

A parallel strand of the literature has emphasised that renovation planning should not rely on operational indicators alone. Life-cycle assessment (LCA) provides a framework to quantify environmental impacts associated with both materials and energy use over the life cycle [12]. Empirical and scenario-based retrofit studies show that deep-renovation

strategies and renewable-based upgrades can substantially reduce operational impacts while also increasing upfront embodied burdens [13–15]. Recent reviews of renovation-LCA research confirm that the field has expanded significantly, but also highlight persistent variation in scope, functional unit, and system boundary, which complicates comparison and limits direct use in decision making [14,16]. More broadly, life-cycle sustainability reviews argue that robust renovation assessment should integrate performance across time and across life-cycle stages, especially when comparing alternative pathways rather than isolated measures [14].

This issue is especially important at the portfolio level. For public or institutional building owners, the key question is not only which measure performs well in an individual building, but how different interventions should be prioritised across a heterogeneous stock. Recent portfolio-oriented studies therefore emphasise the value of decision frameworks that integrate energy, cost, and carbon to reduce ambiguity in renovation choices and support sequencing across buildings [17,18]. At the same time, studies on public and social housing retrofit stress that low-carbon renovation pathways are shaped by practical constraints related to affordability, resident vulnerability, organisational capacity, and the uneven recoverability of investments [19]. These considerations reinforce the need for stock-level sustainability assessments that can compare renovation pathways in a way that is transparent enough to support real-world prioritisation.

In this context, the present study addresses the need for stock-level evidence that explicitly captures the operational-embodied trade-off across alternative renovation pathways for public housing. Product-stage embodied carbon is reported as GWP (A1–A3) and combined with operational emissions (B6) through derived indicators, including carbon payback and horizon-based partial life-cycle climate indicator, PLC(H), based on A1–A3 + B6. This yields a screening-level life-cycle perspective focused on A1–A3 and B6, which should be interpreted as a partial assessment rather than a full EN 15978 [20] whole-life carbon appraisal.

Accordingly, this paper evaluates the portfolio-scale impacts of INFINITE industrialised renovation kits for the public residential building stock managed by EVhA | Entitat Valenciana d'Habitatge i Sòl (Valencian Housing and Land Authority) in the Comunitat Valenciana (Spain), benchmarking them against conventional renovation packages implementable under RENEUEVA and selected as the closest counterparts. A bottom-up stock modelling workflow is applied: operational performance is quantified using CERMA [21] (energy demand, non-renewable primary energy consumption—EP_{nren}, and operational CO₂; module B6), and product-stage embodied carbon is assessed using TURIA [22] and reported as GWP (A1–A3). To connect upfront impacts with operational benefits, we compute (i) a carbon payback period and (ii) a partial life-cycle climate indicator (A1–A3 + B6) evaluated at the 2030, 2035 and 2050 horizons.

The main contributions of the study are threefold: (1) a kit-led scenario design with paired conventional counterparts (S_x ↔ Kit_x) suitable for stock-level interpretation; (2) a quantification of how industrialised and conventional strategies differ in operational indicators and product-stage embodied carbon, highlighting trade-offs across time horizons; and (3) an interpretation framework to support evidence-based renovation prioritisation and sequencing in public-housing portfolios, without implying full whole-life carbon appraisal beyond the adopted boundary.

Therefore, to strengthen the analytical focus, the study is structured around three research questions. RQ1: How do industrialised retrofit kits and their closest counterpart conventional scenarios differ in operational performance and product-stage embodied carbon at the building stock level? RQ2: How do the relative merits of these renovation pathways change across the 2030, 2035, and 2050 horizons under the adopted

partial life-cycle boundary (A1–A3 + B6)? RQ3: What do these results imply for sustainable portfolio-level renovation planning and sequencing in public housing? In this way, the paper contributes a stock-level perspective on how operational decarbonisation, upfront embodied carbon, and decision horizon interact in the design of sustainable renovation strategies.

2. Materials and Methods

The methodological workflow (Figure 1) follows a bottom-up stock modelling approach [23].

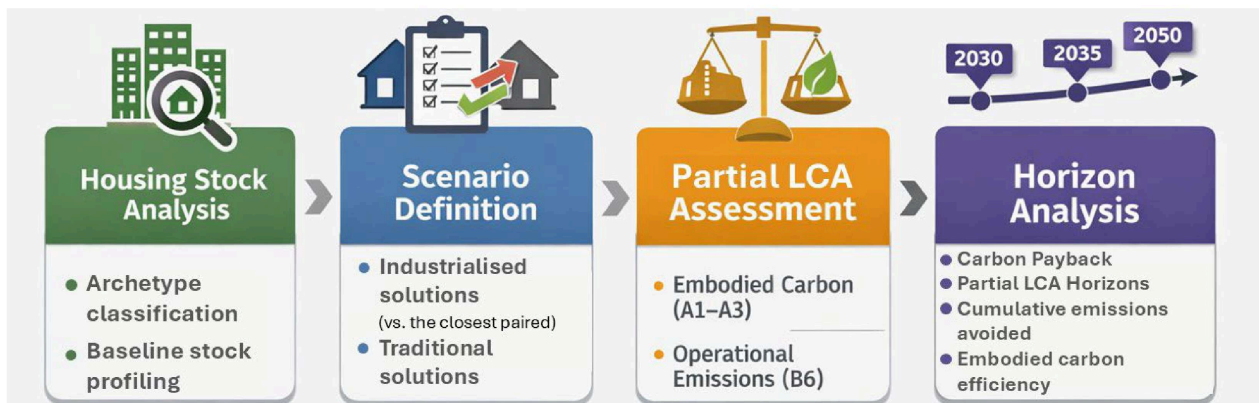


Figure 1. Methodological workflow of the study.

First, EVhA buildings are assigned to RENUVEVA [24] reference archetypes based on construction period, number of floors, and climate cluster, and are aggregated by floor area. Second, baseline and renovation scenarios (Kit 1–Kit 5 and S1–S5) are defined. Third, these scenarios are modelled in CERMA (v5.11) to obtain operational indicators, namely energy demand, non-renewable primary energy consumption (EP_{nren}), and operational CO₂ emissions (module B6). Then, product-stage embodied carbon is quantified using TURIA (v1) and reported as GWP (A1–A3). Finally, the results are aggregated to stock level and combined through derived indicators, including the carbon payback period, defined as GWP (A1–A3) divided by annual CO₂ savings (B6), and a partial life-cycle climate indicator, PLC(H), evaluated at the 2030, 2035 and 2050 horizons. The main steps, inputs, tools, and outputs of this workflow are summarised in Table 1. The industrialised solutions considered correspond to the renovation kits described in INFINITE [25], a Horizon 2020-funded project that develops and demonstrates integrated, prefabricated deep-renovation solutions combining envelope and building services.

2.1. Study Area and Building Stock Dataset

This study assesses the potential impact of alternative renovation strategies applied to the public residential building stock managed by EVhA in the Comunitat Valenciana (Spain). The Comunitat Valenciana is the third Spanish region by number of dwellings within the national housing stock [26], which makes it a relevant case for regional-scale renovation planning. The average age of the EVhA stock in the region is 48 years, indicating a predominance of buildings constructed prior to modern thermal regulations and, therefore, a high potential for energy retrofit.

Table 1. Simplified overview of the methodology.

Step	Main Input/Decision	Tool/Method	Main Output
1. Housing stock definition	Public residential stock in the Comunitat Valenciana	Building dataset + RENU EVA archetypes	Stock mapped by typology, period, climate cluster, and number of floors
2. Baseline definition	Representative existing systems and energy carriers by archetype	CERMA baseline assumptions	Current stock energy demand, EP _{nren} , and operational CO ₂ emissions (B6)
3. Renovation scenarios	Five industrialised kits (Kit 1–Kit 5) and five paired * conventional scenarios (S1–S5)	Scenario design based on INFINITE kits and RENU EVA options	Comparable renovation pathways for assessment *
4. Operational assessment	Baseline + renovation scenarios	CERMA	Energy demand, EP _{nren} , and operational CO ₂ emissions (B6)
5. Embodied-carbon assessment	Renovation measures and products	TURIA	Product-stage embodied carbon, GWP (A1–A3)
6. Combined indicators	Operational + embodied results	Calculated indicators	Carbon payback; partial life-cycle climate indicator, PLC(H); cumulative emissions avoided, E _{avoided} ; embodied-carbon efficiency ECI(H);
7. Horizon-based interpretation	Results evaluated in 2030, 2035, and 2050	Partial life-cycle comparison	Ranking of renovation pathways over different decision horizons

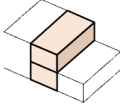
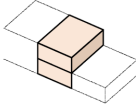
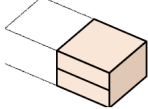
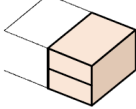
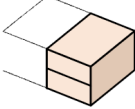
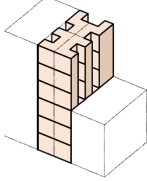
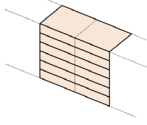
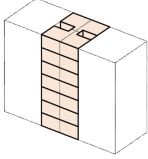
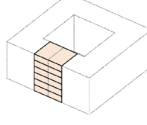
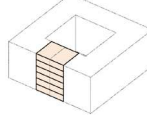
* The scenarios are paired but not perfectly equivalent (see Section 2.4).

The assessed portfolio comprises a total net floor area of 2,274,676 m² and is represented using a bottom-up archetype approach, where each building is mapped to reference typologies by construction period and number of floors (single-family and multi-family archetypes) consistent with the RENU EVA framework (detailed in Section 2.2). The portfolio includes 4334 buildings (35,916 dwellings), extracted from EVhA records in 2021, and is fully mapped to RENU EVA archetypes for simulation and aggregation. The building stock dataset used in this work includes, at a minimum, the building attributes required for archetype assignment (construction period and typology), location-dependent climate classification (RENU EVA climate cluster), and total net floor area for aggregation. Buildings corresponding to the most recent period not covered by the analysis (e.g., 2008–2013 reference archetypes) are excluded, as stated in Table 2.

2.2. Stock Modelling Framework and Archetypes

A bottom-up stock modelling approach is employed, in which operational performance—including energy demand, non-renewable primary energy, and operational CO₂ emissions—is estimated for individual building archetypes and then aggregated to the stock level. The building stock is mapped to the reference typologies used in RENU EVA, a free online tool developed by the Valencia Institute of Building (IVE) that provides a rapid energy pre-assessment of existing buildings and suggests renovation measures for the envelope and building systems. Typologies are defined by construction period and number of floors, following the typological framework of Spain’s long-term renovation strategy (ERESEE) [27]. Reference archetypes include single-family houses (SFH) and apartment blocks (AB) (Table 2).

Table 2. Reference building types.

Typology Code	SFH.01	SFH.02	SFH.03	SFH.04	SFH.05
Volumetric modelling					
Construction period	<1940	1941–1960	1961–1980	1981–2007	2008–2013 *
Number of floors	≤2	≤2	≤2	≤2	≤2
Typology Code	AB.01	AB.02	AB.03	AB.04	AB.05
Volumetric modeling					
Construction period	<1940	1941–1960	1961–1980	1981–2007	2008–2013 *
Number of floors	≥3	≥3	≥3	≥3	≥3

* For the purposes of this study, SFH.05 and AB.05 buildings have not been considered in the analysis.

In RENEVA, the Spanish territory is divided into four climate clusters according to winter and summer climatic severity associated with the underlying climate zones of the Spanish Technical Building Code (CTE) [28], which depend on province and altitude. These clusters enable assigning different construction characteristics to the same archetype family under different climatic conditions. The mapping between climate zones and clusters at the national level, and the corresponding climate zones present in the Comunitat Valenciana region, is reported in Table 3. In this study, the analysed EVhA buildings fall within clusters B and C, specifically including buildings in B3–B4 climate zones (cluster B) and C2–C3–D2–D3 climate zones (cluster C).

Table 3. Climate zones per clusters in Spain and the Comunitat Valenciana region.

	Cluster A	Cluster B	Cluster C	Cluster D
Spain	α3, A4, A3, A2	B2, B3, B4	C1, C2, C3, C4, D2, D3	D1, E1
Comunitat Valenciana	-	B3, B4	C2, C3, D2, D3	

The total net floor area of the assessed building stock amounts to 2,274,676 m². After the archetype assignment, the distribution of net internal floor area across typologies and the two climate clusters is reported in Table 4. The AB.03 typology is the most prevalent, accounting for 31% of the total area, and therefore plays a major role in the aggregated stock-level results.

Table 4. Net internal floor area (m²) per reference building type and climate cluster.

Climate Cluster	SFH.01	SFH.02	SFH.03	SFH.04	AB.01	AB.02	AB.03	AB.04
B	147	29,434	26,492	13,281	3273	285,878	712,519	665,087
C		42,626	26,852	26,670		35,919	141,042	265,455

Empty cell indicates that there are no buildings of the specified type.

Baseline systems and energy carriers assigned to each archetype–cluster combination are described in Section 2.3.

2.3. Baseline Assumptions (Systems and Energy Carriers)

Baseline assumptions for existing heating, ventilation and air conditioning (HVAC) and domestic hot water (DHW) systems are defined according to regional evidence on system prevalence by building type and construction period (Table 5). In the RENEVA tool, users select the building’s existing technical systems to best match a specific building configuration. In a stock-level application such as the present study, building-level system information is not available with sufficient granularity for every asset; therefore, baseline systems are assigned by archetype and construction period using the most common and representative installations observed in the regional context. Based on INE (2021) [29–31] and complemented by IDAE (2019) [32], collective systems and renewable contributions are assumed to be marginal in the residential stock and are therefore not considered in the baseline. Accordingly, the baseline system assignments are defined using electric end-use systems for space conditioning: electric radiators are assumed for space heating in all single-family house (SFH) archetypes, reflecting the frequent lack of fixed heating installations, whereas reversible heat pumps are assumed for space heating in all apartment block (AB) archetypes where individual systems prevail. Cooling is assumed to be absent in SFH.01–SFH.02 and provided by reversible heat pumps in SFH.03–SFH.04 and across all AB archetypes, consistent with segments where active cooling is widespread. Domestic hot water is assumed to be individual in all cases, represented by electric water heaters in SFH archetypes and gas water heaters in all AB archetypes.

Table 5. Assigned baseline HVAC and DHW systems by archetype and building type.

System	SFH.01	SFH.02	SFH.03	SFH.04	AB.01	AB.02	AB.03	AB.04
Heating	ER	ER	ER	ER	ERHP	ERHP	ERHP	ERHP
Cooling	-	-	ERHP	ERHP	ERHP	ERHP	ERHP	ERHP
DHW	EWH	EWH	EWH	EWH	GWH	GWH	GWH	GWH

ER: Electric radiator; ERHP: Reversible heat pump; EWH: Electric water heater; GWH: Gas water heater.

2.4. Renovation Scenarios

Two families of renovation strategies are evaluated: industrialised renovation kits (Kit 1–Kit 5) and conventional on-site renovation measures (S1–S5). Scenario definitions are summarised in Table A1 and were designed to cover three increasing levels of intervention ambition: (i) envelope-only upgrades, (ii) deep retrofit including systems substitution and indoor-air strategy, and (iii) integration of on-site renewable electricity generation.

Scenario design and pairing logic. The renovation scenarios were designed following a kit-led approach: INFINITE industrialised kits (Kit 1–Kit 5) were defined first, and conventional RENEVA measures were then selected to approximate the scope and ambition of each kit, resulting in paired conventional scenarios (S1–S5). This pairing supports a like-for-like interpretation of industrialisation effects, while acknowledging that strict functional equivalence is not always possible.

2.4.1. Industrialised Renovation Kits (Kit 1–Kit 5)

Industrialised solutions correspond to the INFINITE renovation kits, conceived as pre-fabricated, façade-integrated modules that can combine envelope upgrading with building services and on-site renewables:

- Kit 1—Passive eco-compatible and green envelope kit: An industrialised green envelope solution is a system targeting optimised manufacturing and installation

of façade elements, including insulation with green cladding and a roof module. The concept may be coupled with a rooftop photovoltaic panel (PV) (not considered for this study) and includes additional components for irrigation management (e.g., grey-water/rainwater treatment and bio-electrochemical systems) and environmental sensing.

- Kit 2—Energy and fresh air distribution kit: A façade-integrated solution that, in addition to insulation, provides fresh air, heating and cooling through decentralised ventilation units with heat recovery and water coils, façade-integrated ducts and hydraulic connections to a centralised heat pump, and sensing/control components intended to regulate air and energy distribution based on indoor conditions.
- Kit 3—Smart window kit: It is a smart/adaptive glazing solution integrated in a smart frame, pre-installed within the prefabricated façade module. The concept includes sensor-driven dynamic blind control and/or electrochromic (plasmochromic) glazing, with a control algorithm aimed at reducing energy demand while maintaining visual and thermal comfort.
- Kit 4—BIPV kit: A prefabricated envelope retrofit kit that combines an insulated façade module with a plug-and-play building-integrated PV (BIPV) system for roof and façade integration on prefabricated supporting structures, designed to reduce on-site installation time. The concept also includes an energy-management layer to optimise energy flows between on-site generation, storage and the grid.
- Kit 5—Integrated kit: A combined deployment of Kits 1–4, integrating the green envelope solution, energy and fresh air distribution, smart windows and BIPV within a single renovation concept.

Modelling scope note: In this study, the operational performance assessment (CERMA) represents the effects of the kits through equivalent modelling constructs for envelope properties, ventilation with heat recovery, shading control, heat pump systems and PV (Section 2.5). Components such as grey-water treatment/BES, embedded sensors, user interfaces and advanced energy-management functions are described as part of the INFINITE concept but are not explicitly quantified in the energy and carbon calculations reported here.

Figure 2 illustrates the INFINITE industrialised retrofit concept and the kit family (Kit 1–Kit 5).

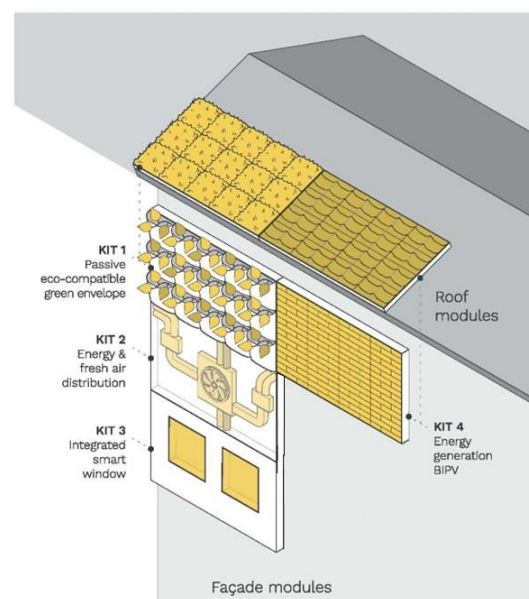


Figure 2. INFINITE industrialised retrofit concept and kit family (Kit 1–Kit 5).

2.4.2. Conventional Renovation Measures (S1–S5)

Conventional measures represent RENU EVA-implementable on-site renovation packages selected as the closest counterparts to each kit within the tool's scope:

- S1 (paired to Kit 1): Thermal insulation of the opaque envelope (façade and roof; including party walls where applicable), without window replacement.
- S2 (paired to Kit 2): Opaque envelope insulation (façade and roof) plus window replacement, and substitution of thermal systems by an air-source heat pump solution for heating, cooling and DHW.
- S3 (paired to Kit 3): Window replacement only (no opaque-envelope insulation).
- S4 (paired to Kit 4): Opaque envelope insulation (façade and roof) without window replacement, plus rooftop PV installation.
- S5 (paired to Kit 5): Opaque envelope insulation (façade and roof) plus window replacement, air-source heat pump systems, and rooftop PV installation.

The $S_x \leftrightarrow \text{Kit}_x$ pairing matches the dominant functional scope of each kit with the closest RENU EVA-implementable conventional package: Kit 1 primarily targets opaque envelope upgrading with green solutions and is paired with S1 (opaque envelope insulation without window replacement); Kit 2 combines envelope and openings upgrading with systems substitution and a fresh-air strategy and is paired with S2 (envelope + windows + aerothermal heat pump); Kit 3 focuses on window performance and solar control and is paired with S3 (windows-only); Kit 4 introduces PV integration alongside envelope upgrading (roof and façade) and is paired with S4 (envelope + rooftop PV); and Kit 5 represents an integrated deep retrofit package and is paired with S5 (envelope + windows + systems + rooftop PV). Residual differences in functional scope (e.g., rooftop PV versus roof+façade BIPV) are addressed explicitly as comparability caveats in Section 2.4.3. A detailed description of the renovation packages and pairwise mapping is provided in Table A1 (Appendix A).

2.4.3. Comparability Caveats

Although the $S_x \leftrightarrow \text{Kit}_x$ pairing is used to approximate comparable scopes, strict one-to-one functional equivalence cannot always be ensured. To provide a transparent basis for evaluating the trade-offs, Table 6 explicitly lists the functional scope matched across each pair and the specific unmatched components. The main comparability limitations are as follows: (i) PV integration scope differs for the $S_4 \leftrightarrow \text{Kit}_4$ and $S_5 \leftrightarrow \text{Kit}_5$ pairs, as S_4 and S_5 include rooftop PV only, whereas Kit_4 and Kit_5 integrate PV on both roof and façade; therefore, this pair should be interpreted as alternative PV integration strategies rather than a pure “industrialised vs traditional” comparison. (ii) Kit_2 (and Kit_5) includes mechanical ventilation with heat recovery (MVHR) as part of an integrated indoor-air strategy, which is not mirrored in the paired conventional package.

These differences reflect the fact that the conventional scenarios were selected to represent typical RENU EVA-implementable renovation packages, whereas some kit components (e.g., façade BIPV integration or MVHR) are not commonly included in conventional renovations at scale. Accordingly, results are interpreted with explicit reference to these scope differences, discussing their implications for both operational performance (B6) and product-stage embodied carbon (A1–A3), and for the time-horizon indicators (Sections 3 and 4).

Table 6. Comparison matrix of matched and unmatched functions per scenario pair.

Pairwise Comparison	Renovation Level Focus	Matched Functions (Included in Both)	Unmatched Functions (Included in Kit, Absent in Sx)
Kit 1 vs. S1	(i) Envelope-only	Envelope insulation	Green finishes (S1 uses standard opaque insulation)
Kit 2 vs. S2	(ii) Deep retrofit	Envelope insulation, window replacement, air-source heat pump (H/C/DHW)	Mechanical Ventilation with Heat Recovery (MVHR) (S2 relies on baseline ventilation)
Kit 3 vs. S3	(i) Envelope-only	Window replacement	Dynamic/smart shading control (S3 uses standard windows without automated shading)
Kit 4 vs. S4	(iii) Renewables	Envelope insulation, rooftop PV	Façade-integrated BIPV (S4 includes rooftop PV only)
Kit 5 vs. S5	(iii) Renewables	Envelope insulation, window replacement, air-source heat pump, rooftop PV	Green finishes, dynamic shading, MVHR, and Façade BIPV (S5 lacks MVHR and façade BIPV)

(i) Envelope-only upgrades; (ii) deep retrofit; (iii) integration of on-site renewable electricity generation.

2.5. Operational Performance Modelling

2.5.1. Simulation Approach and Reported Operational Indicators

Operational performance is modelled using CERMA, an official Spanish tool for building-energy certification procedures. For each archetype and climate cluster, CERMA simulations are run for the current stock baseline and for each renovation scenario. Results are aggregated to the stock level to compute: (a) annual total energy demand (MWh/y), (b) annual non-renewable primary energy consumption, EP_{nren} (MWh/y), and (c) annual operational CO₂ emissions (tCO₂/y). Savings are computed relative to the current stock baseline.

Non-renewable primary energy conversion and operational CO₂ emission factors used to compute EP_{nren} and operational emissions (B₆) are taken from the CTE/CERMA default conversion factors (MITECO/RITE recognised document; application from 14 January 2016 [33]) and applied consistently across all scenarios (scenario-invariant). Table 7 reports the EP_{nren} conversion factors and operational CO₂ emission factors applied by energy carrier.

Table 7. Conversion factors by energy carrier.

Energy Carrier (Final Energy)	EP _{nren} Conversion Factor (kWh _{p,nren} /kWh _{Final})	Operational CO ₂ (kgCO ₂ /kWh _{Final})
Grid electricity (Peninsular)	1.954	0.331
Natural gas	1.190	0.252

CERMA accounts for on-site PV by calculating the monthly photovoltaic energy compensated through self-consumption, which directly reduces the building's electricity demand from the grid in the EP_{nren} and operational CO₂ (B₆) calculations. The compensated PV generation is allocated proportionally across end-uses/services according to their electricity consumption. PV production in excess of the building's electricity consumption is treated as surplus and is not credited within the building's energy and emissions balance under the CERMA methodology.

2.5.2. Representation of INFINITE Kits in CERMA

CERMA is an official certification-oriented tool that offers a widely adopted framework for assessing operational performance. Its level of detail is aligned with certification practice, which supports consistency and comparability across scenarios at the stock level. However, some INFINITE technologies require modelling approximations, and certain phenomena (e.g., evapotranspiration or opaque-façade shading effects of living envelopes) cannot be represented exhaustively within the software structure. Accordingly, the INFINITE kits are implemented using equivalent modelling constructs that represent the dominant energy-relevant mechanisms (envelope thermal properties, ventilation heat recovery, shading control and PV generation). The key modelling assumptions and parameter values used to implement these representations are as follows:

- Kit 1—Passive eco-compatible & green envelope: The green wall and roof are represented by adding a soil layer of 13 cm in the façade and 9.5 cm in the roof, and adjusting façade and roof to clear colour to increase albedo. The modelling captures thermal mass/insulation effects of the layer and reflectance changes, but does not capture the shadowing effect on opaque façades or evapotranspiration explicitly.
- Kit 2—Energy and fresh air distribution: The façade-integrated module is represented in CERMA by combining a façade insulation upgrade with mechanical ventilation with heat recovery (MVHR). Heat-recovery efficiency is set to 80% (INFINITE data). The MVHR airflow rate is calculated by CERMA to comply with the CTE HS3 minimum ventilation requirements for the dwelling typology. A bypass control is implemented using the rule $15\text{ }^{\circ}\text{C} < T_{\text{ext}} < 22\text{ }^{\circ}\text{C}$, and night-time natural ventilation is maintained at 4 ACH during the summer months alongside MVHR.
- Kit 3—Smart window: The improved solar control delivered by Kit 3 through automatic/dynamic shading is modelled in CERMA by upgrading the mobile shading element control to an automatic strategy: active 90% when the façade receives direct solar radiation during daytime, and inactive at night, with operation only triggered by cooling demand (summer mode).
- Kit 4—BIPV: The plug-and-play PV kit is represented in CERMA by adding roof and façade PV sized from the available opaque façade/roof surface of each archetype after subtracting window openings and applying a waste/coverage coefficient (i.e., effective PV area = opaque area \times coverage factor). PV capacity is then derived using a constant module area and nominal peak power per module (panel “brown”), converting the resulting number of panels into total installed kWp. Façade PV is modelled as vertical (tilt $\approx 90^{\circ}$) with an azimuth representative of the main façade (e.g., -45°), and roof PV follows the standard rooftop assumptions used in RENEUEVA; other PV performance parameters are kept as CERMA defaults.
- Kit 5—Integrated kit: Kit 5 represents the combined deployment of Kits 1–4; therefore, its CERMA representation applies the same modelling assumptions adopted for all the kits implemented consistently within a single scenario.

2.6. Embodied-Carbon Assessment

2.6.1. Goal, Scope and Reporting Boundary

The goal of the LCA analysis is to provide a screening, comparative assessment of the upfront embodied greenhouse gas emissions associated with the renovation solutions assessed. The embodied results reported in this paper are limited to product-stage embodied carbon, expressed as GWP (tCO₂e) for modules A1–A3, and therefore do not constitute a whole-life carbon assessment (WBLCA) under EN 15978. Construction stage (A4–A5), additional use-stage modules beyond B6 (e.g., replacements), and end-of-life stages (C/D)

are outside the embodied reporting boundary adopted in this manuscript. The life-cycle stages considered in the building assessment are shown in Figure 3.

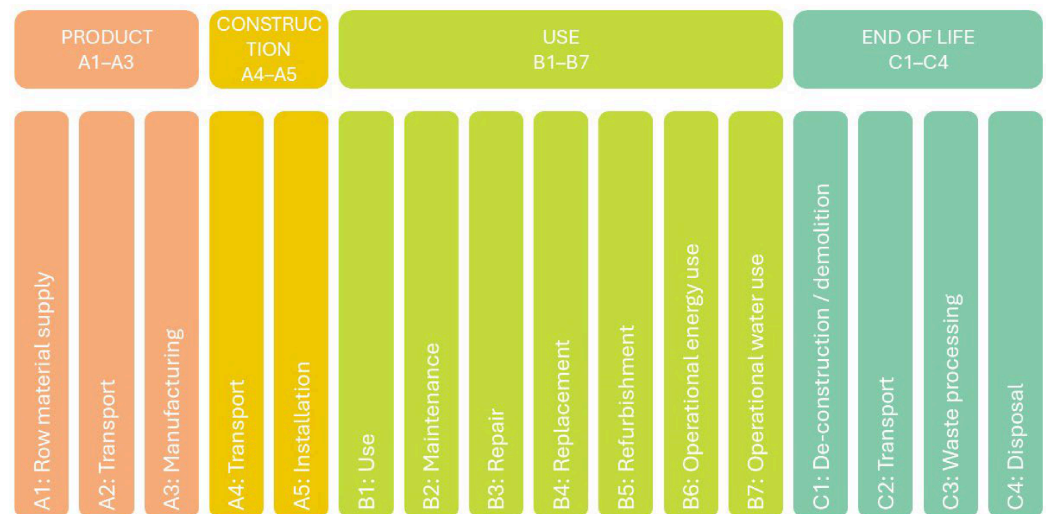


Figure 3. Stages of the building assessment (figure adapted from TURIA user manual [22]).

2.6.2. Functional Unit, Data Source and Impact Indicator

The functional unit is defined as the implemented renovation measures required to deliver the assessed performance improvement for the analysed building (i.e., the set of components and materials installed to achieve the targeted envelope and system upgrade), applied consistently across all compared options and aggregated to the stock level. Embodied emissions are modelled with TURIA, a free web-based tool developed by the Valencia Institute of Building (IVE) that generates environmental assessment reports for building and civil engineering projects and supports the integration of life-cycle environmental criteria in procurement. TURIA follows the EN 15978 modular structure, and this study covers the product and construction stages (A1–A5). The reported impact indicator is global warming potential (GWP) expressed as kg CO₂e (and aggregated to stock level as tCO₂e). For the INFINITE kits, quantities and product information were provided by kit developers/manufacturers, and the LCA study carried out in the framework of the project followed ISO standards 14040 and 14044, while conventional renovation measures were modelled using IVE's Construction Database (BDC) [34] and TURIA's datasets, whose values come from EPDs from the UNE-EN 15804:2012+A1:2014 and UNE-EN 15804:2012+A2:2020 standards [35,36]. To preserve comparability in this screening assessment, all options are evaluated under the same system boundary, impact indicator (GWP), and modelling assumptions within TURIA, and dataset choices are applied consistently wherever equivalent information is available. This mixed-data approach may affect absolute values, but it improves representativeness for the kits while maintaining internal consistency for comparative interpretation.

To improve transparency regarding the embodied-carbon inputs used in the comparative assessment, Table 8 summarises the source type, level of specificity, and harmonisation assumptions adopted for the two scenario families.

Table 8. Embodied-carbon data pedigree and harmonisation by scenario family.

Scenario Family	Source Type	Level of Specificity	Harmonisation Assumption
Conventional renovation scenarios (S1–S5)	BDC IVE/TURIA datasets	Generic database-based	Compared under the same GWP (A1–A3) reporting boundary, impact indicator, and screening-level comparative framework
Industrialised renovation kits (Kit 1–Kit 5)	Manufacturer/developer-provided information	Project-/manufacturer-specific	Compared under the same GWP (A1–A3) reporting boundary, impact indicator, and screening-level comparative framework

As shown in Table 8, the embodied-carbon comparison combines project- or manufacturer-based inputs for the industrialised kits with generic database-based inputs for the conventional scenarios. Comparability is maintained through the use of a common GWP (A1–A3) reporting boundary, a shared impact indicator, and consistent screening-level interpretation across all scenarios; however, absolute values should be interpreted with caution when reading precise pairwise embodied-carbon differences.

2.6.3. Exclusion of A4–A5 and Interpretation Implications

Although TURIA can provide information for A1–A5, this paper reports embodied impacts for A1–A3 only. Modules A4–A5 (transport to site and construction/installation processes) are excluded because they are highly dependent on project- and location-specific implementation conditions (e.g., supply-chain routes and transport distances, site access constraints, installation planning and productivity, and on-site waste management). In a stock-level assessment, these conditions vary widely across buildings and renovation programmes. Therefore, representing A4–A5 would require robust and representative programme-level assumptions (e.g., distributions of transport distances, site constraints and installation productivity) for each assessed alternative; without such assumptions, including A4–A5 risks introducing non-representative variability and biasing comparisons.

Excluding A4–A5 improves comparability but may influence the relative ranking; industrialised solutions may reduce on-site waste and time (A5), while logistics (A4) may differ depending on delivery distances and modes. Any statements about longer-term performance are therefore limited to partial life-cycle indicators combining GWP (A1–A3) with operational emissions (B6) over the adopted horizons (Section 2.7).

2.7. Derived Indicators and Time Horizons

To connect upfront product-stage embodied impacts with operational benefits, two derived indicators are calculated: (i) a carbon payback period, and (ii) a partial life-cycle climate indicator combining GWP (A1–A3) with cumulative operational emissions (B6) over defined time horizons. These indicators are computed at the stock level, using the same aggregation basis as the operational and embodied results.

2.7.1. Definition and Calculation of the Carbon Payback Period

The carbon payback period expresses how quickly the upfront product-stage embodied emissions of a renovation option are compensated by its annual operational CO₂ savings. It is defined as:

$$T_{\text{CO}_2} = \frac{\text{GWP}(\text{A1} - \text{A3})}{\text{CO}_{2,\text{savings,annual}}}$$

where T_{CO_2} is the carbon payback time (years), $GWP(A1 - A3)$ is the upfront embodied GWP associated with the renovation option (product-stage modules A1–A3, in tCO_2e), and $CO_{2,savings,annual}$ is the annual reduction in operational CO_2 emissions attributable to the renovation (module B6, in tCO_2/y). In this study, annual operational CO_2 savings are computed as:

$$CO_{2,savings,annual} = CO_{2,baseline,B6} - CO_{2,scenario,B6}$$

Payback values, therefore, depend on both the magnitude of the upfront A1–A3 “carbon investment” and the annual operational CO_2 savings delivered in use. The indicator is intended as a transparent time-based metric to interpret front-loaded embodied impacts versus annual operational reductions within the adopted boundary.

2.7.2. Partial Life-Cycle Climate Indicator

In addition to payback, a horizon-based cumulative metric is computed to reflect the different time profiles of GWP (A1–A3) and operational emissions (B6). For each scenario, the partial life-cycle climate indicator at a given horizon H is calculated as:

$$PLC(H) = GWP(A1 - A3) + \sum_{t=1}^H CO_{2,scenario,B6}(t)$$

In practice, operational emissions are treated as annual totals and accumulated over the selected horizons. In this study, the indicator is evaluated at the 2030, 2035 and 2050 horizons. The reference year for the operational baseline is 2026; therefore, the horizons correspond to $H = 4$ years (2030), $H = 9$ years (2035) and $H = 24$ years (2050). The indicator enables comparing renovation options under short-, mid- and long-term perspectives, highlighting cases where high upfront impacts require longer horizons for operational savings to dominate.

This horizon-based indicator complements carbon payback. While payback summarises the time-to-compensation of upfront GWP (A1–A3) through annual savings, the cumulative indicator explicitly shows how total (A1–A3 + B6) outcomes evolve at milestone years, supporting interpretation of near-term versus long-term climate performance within the partial boundary adopted in this study.

2.7.3. Cumulative Emissions Avoided

To express cumulative benefits relative to the current stock, we compute cumulative emissions avoided at each horizon as:

$$E_{avoided}(H) = PLC(H)_{current} - PLC(H)_{scenario}$$

Positive values indicate lower cumulative $PLC(H)$ than the current stock by the milestone, while negative values indicate that upfront GWP (A1–A3) impacts have not yet been compensated within the assessed boundary.

2.7.4. Embodied Carbon per Unit Benefit

To express the upfront effort required per unit of cumulative benefit at a given horizon H , we report $GWP(A1-A3)$ per tCO_2e avoided as:

$$ECI(H) = \frac{GWP(A1-A3)}{E_{avoided}(H)}$$

where $E_{avoided}(H)$ is defined in Section 2.7.3. This ratio is reported only when $E_{avoided}(H) > 0$; lower values indicate higher carbon efficiency.

2.8. Uncertainty and Limitations (Method-Level)

Results should be interpreted within the adopted modelling choices and system boundary. To support comparability across alternatives, embodied carbon is reported for A1–A3 only; construction (A4–A5), additional use-stage modules beyond B6 (e.g., replacements), and end-of-life stages (C/D) are excluded. Operational results are obtained with CERMA and represent INFINITE technologies through equivalent modelling constructs, meaning that some phenomena (e.g., evapotranspiration or opaque-façade shading for living envelopes) are not modelled explicitly. PV effects are reflected through CERMA’s accounting of on-site generation against electricity consumption. Finally, EP_{nren} and operational CO₂ are computed using CTE/CERMA factors applied consistently across scenarios; therefore, horizon-based results use time-invariant operational factors (i.e., it does not model future changes in grid-emission intensity). To test the sensitivity of long-horizon results to electricity-related assumptions, an additional bounded sensitivity analysis is reported in Appendix B. Annual operational CO₂ emissions (B6), carbon payback and PLC(H) are recalculated under alternative electricity-emission-factor cases representing current, moderate and strong electricity decarbonisation, while keeping natural-gas factors and GWP (A1–A3) unchanged. In addition, to test the sensitivity of the long-horizon interpretation to embodied-boundary choices beyond A1–A3, a second bounded sensitivity analysis is reported in Appendix C. This additional test applies simple indicative burdens for A4–A5 and, where relevant, replacement-heavy components, expressed as percentages of reported GWP (A1–A3), in order to assess whether plausible downstream additions could materially affect comparative results.

During the preparation of this manuscript, the authors used ChatGPT-5.4 (OpenAI) to assist in drafting selected parts of the text and in the preparation of data visualizations. It was not used for study design, data collection, data analysis, or interpretation of results. All outputs were reviewed, edited, and validated by the authors, who take full responsibility for the final content of this publication.

3. Results

This section reports the results in direct relation to the study’s research questions. First, it examines how the industrialised retrofit kits and their paired conventional scenarios differ in operational performance and product-stage embodied carbon at the stock level (RQ1). Second, it analyses how the relative merits of these renovation pathways change across the 2030, 2035 and 2050 horizons under the adopted partial life-cycle boundary, which combines GWP(A1–A3) with operational emissions (B6) (RQ2). Third, it identifies what these results imply for sustainable portfolio-level renovation planning and sequencing in public housing (RQ3). All scenarios are evaluated consistently for the same building stock and compared against the current baseline stock.

3.1. RQ1—Operational and Product-Stage Embodied Outcomes Across Renovation Pathways

3.1.1. Stock-Level Operational Performance

Operational indicators show substantial differences across scenarios, reflecting both the depth of envelope upgrading and the degree of systems integration (electrification, ventilation with heat recovery and PV). Table 9 summarises the stock-level outcomes for energy demand, EP_{nren} (Non-renewable primary energy consumption) and operational CO₂ emissions, including savings relative to the current stock baseline.

Table 9. Summary of the impacts according to the different renovation scenarios.

Impacts	Unit	Current Building Stock	Traditional Renovation Measures					Industrialised Renovation Measures					
			S1	S2	S3	S4	S5	Kit 1	Kit 2	Kit 3	Kit 4	Kit 5	
Operational performance (B6)	Energy demand	MWh/y	171,024	106,932	85,685	152,978	106,928	85,685	105,762	70,629	142,207	106,931	58,281
	Demand savings	%	N/A	37	50	11	37	50	38	59	17	37	66
	EPnren	MWh/y	211,878	149,538	49,400	191,360	95,686	4001	148,412	38,090	181,596	88,025	6
	EPnren savings	%	N/A	29	77	10	55	98	30	82	14	58	100
	Operational CO ₂ emissions	tCO ₂ /y	39,125	28,526	8382	35,631	19,407	702	28,334	6445	33,968	18,102	1
Operational CO ₂ savings	%	N/A	27	79	9	50	98	28	84	13	54	100	
Embodied carbon(A1–A3)	GWP (A1–A3)	tCO ₂ e	N/A	93,318	236,509	17,573	115,160	258,351	18,893	384,687	37,651	264,376	485,091
	ΔGWP (A1–A3) (Sx – Kitx)/Sx *	%	N/A	N/A	N/A	N/A	N/A	N/A	80	–63	–114	–130	–88
Derived indicator	T _{CO₂} Carbon Payback	y	N/A	8.8	7.7	5.5	5.8	6.7	1.8	11.8	7.3	12.6	12.4

* For industrialised kits, ΔGWP (A1–A3) vs paired Sx (%) are computed relative to the paired (but not perfectly equivalent) conventional scenario (S1 ↔ Kit 1, . . . , S5 ↔ Kit 5) as:

$$\Delta GWP_{A1-A3}(\%) = \frac{GWP_{Sx} - GWP_{Kitx}}{GWP_{Sx}} \times 100$$

Positive values indicate lower ΔGWP (A1–A3) for the kit; negative values indicate higher ΔGWP (A1–A3). Large magnitudes may occur when GWP_{Sx} is comparatively small.

Across scenarios, demand reductions are primarily driven by envelope measures and solar-control-related improvements, whereas EPnren and operational CO₂ reflect additional effects from system efficiencies, energy carriers and PV self-consumption. As shown in Table 9, the largest reductions in EPnren and operational CO₂ are achieved by the packages combining electrification and PV, while envelope-only packages deliver more moderate reductions.

3.1.2. Product-Stage Embodied Carbon (GWP A1–A3)

The product-stage embodied results also differ markedly across scenarios. Among conventional measures, S5 shows the highest product-stage impact, followed by S2 and S4. Lower GWP (A1–A3) values are observed for S1 and particularly S3. Among industrialised measures, Kit 1 has the lowest product-stage embodied carbon, followed by Kit 3. By contrast, the higher-integration kits show substantially larger GWP (A1–A3) burdens: Kit 2, Kit 4, and especially Kit 5. Taken together, Table 9 indicates that operational decarbonisation and product-stage embodied carbon do not move in parallel: the pathways with the strongest B6 reductions are not necessarily those with the lowest A1–A3 impacts.

3.1.3. Pairwise Interpretation Under Matched and Unmatched Scope

Pairwise comparison helps interpret how the industrialised kits differ from their closest conventional counterparts, but these contrasts must be read in light of the comparability limits defined in Section 2.4.3. Figure 4 illustrates the operational-embodied trade-off across the conventional scenarios and industrialised kits.

In the tighter pairings, especially S1 ↔ Kit 1 and, to a lesser extent, S3 ↔ Kit 3, the comparison is more robust. Kit 1 combines broadly similar operational CO₂ to S1 with substantially lower GWP (A1–A3), indicating a favourable low-upfront-carbon outcome within the adopted boundary. By contrast, the more integrated kits tend to improve operational performance relative to their paired conventional scenarios while increasing upfront embodied carbon. This pattern is visible for Kit 2 and Kit 5, but these comparisons should be interpreted cautiously because the kits include MVHR as part of an integrated indoor-air strategy not mirrored in the paired conventional cases. Similarly, the S4 ↔ Kit 4 and S5 ↔ Kit 5 contrasts should be read as comparisons between alternative PV integration strategies rather than strict industrialised versus conventional equivalents, because the kits integrate PV on both roof and façade, whereas the paired conventional scenarios

include rooftop PV only. Overall, the pairwise results show that industrialisation does not systematically reduce product-stage embodied carbon; rather, outcomes are configuration-dependent and sensitive to the specific scope of integration.

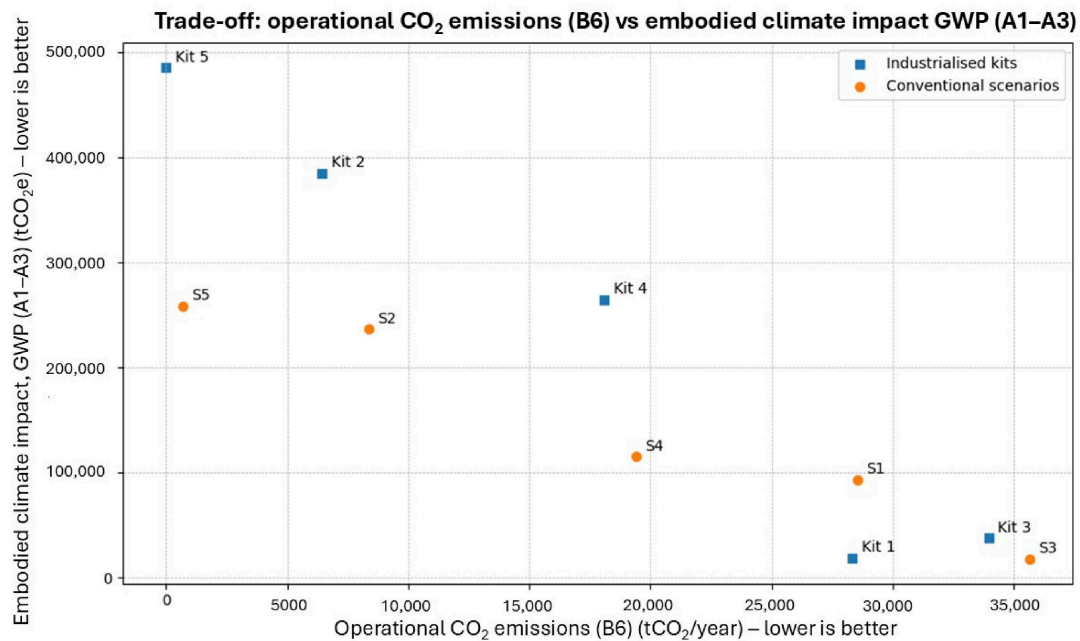


Figure 4. Operational-embodied trade-off: Annual operational CO₂ emissions (B6, tCO₂/y) versus product-stage climate impact (GWP (A1–A3), tCO₂e) for conventional scenarios (S1–S5) and industrialised kits (Kit 1–Kit 5). Note that the scenarios are paired but not perfectly equivalent.

3.2. RQ2—How the Relative Merits of These Renovation Pathways Change with Time Horizon

3.2.1. Carbon Payback Period

Carbon payback translates the operational-embodied balance into a time dimension. As reported in Table 9, options with relatively low GWP (A1–A3) and meaningful annual B6 savings achieve the shortest paybacks, whereas highly integrated packages with high upfront burdens require longer periods for annual operational savings to compensate their initial carbon investment.

Figure 5 synthesises the relationship between operational CO₂, GWP (A1–A3) and payback visually, highlighting the time dimension of the operational-embodied trade-off. Pairwise comparisons indicate that Kit 1 achieves a markedly shorter payback than its paired conventional option (S1), reflecting a lower upfront GWP (A1–A3) burden with comparable operational performance. By contrast, for the more integrated packages, industrialised solutions tend to exhibit longer payback periods than their paired conventional scenarios, consistent with higher product-stage impacts that require longer horizons to be compensated by annual operational savings.

3.2.2. Horizon-Based Partial Life-Cycle Performance

Table 10 reports a time-horizon perspective by combining product-stage impacts, GWP (A1–A3), with cumulative operational CO₂ emissions (B6) for three policy-relevant horizons: 2030 (4 years), 2035 (9 years) and 2050 (24 years). The relative merits of the assessed pathways change materially with the decision horizon because GWP (A1–A3) is incurred upfront, whereas operational CO₂ emissions accumulate annually.

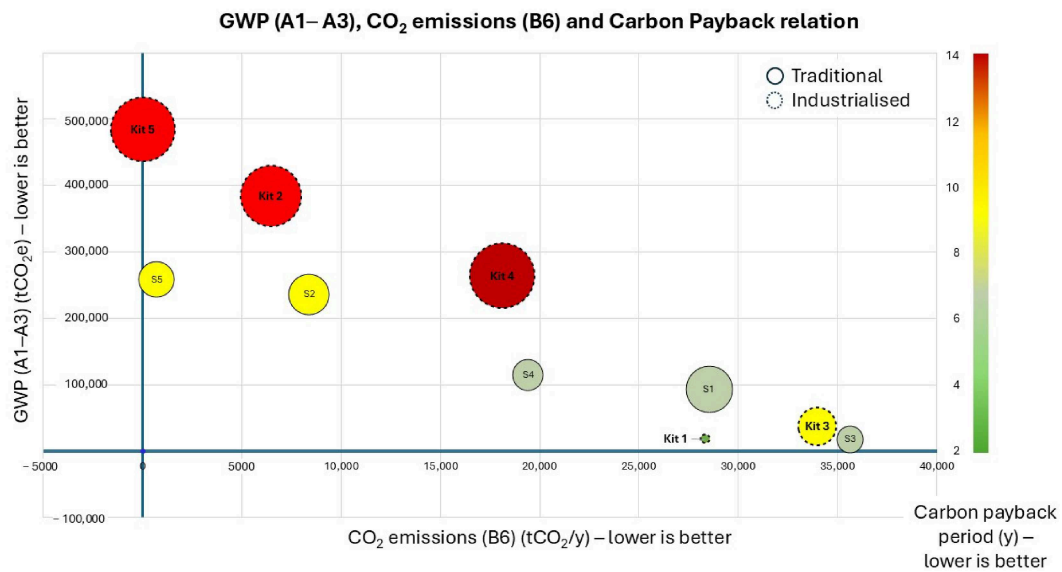


Figure 5. Relationship between GWP (A1–A3) (tCO₂e), annual operational CO₂ emissions (B6, tCO₂/y) and carbon payback (years) for industrialised kits (Kit 1–Kit 5) and conventional scenarios (S1–S5); bubble colour indicates payback period. Note that the scenarios are paired but not perfectly equivalent.

Table 10. PLC(H): Partial life-cycle climate indicator (GWP (A1–A3) + accumulated operational CO₂ emissions (B6)) (tCO₂e) according to renovation scenario and time horizon. PLC(H) is reported as a cumulative total from the reference year (2026) to each milestone; GWP (A1–A3) is counted upfront, and operational CO₂ emissions (B6) are accumulated annually.

Date	Years	Current Building Stock	Traditional Renovation Measures					Industrialised Renovation Measures				
			S1	S2	S3	S4	S5	Kit 1	Kit 2	Kit 3	Kit 4	Kit 5
2030	4	156,499	207,424	270,037	160,097	192,788	261,160	132,230	410,468	173,522	336,782	485,095
2035	9	352,123	350,055	311,949	338,252	289,823	264,672	273,903	442,696	343,361	427,290	485,100
2050	24	938,996	777,949	437,682	872,716	580,928	275,208	698,920	539,377	852,879	698,814	485,117

Table 10 shows that the cumulative partial life-cycle climate indicator, PLC(H), is strongly horizon-dependent. At short horizons, rankings are mainly shaped by whether the initial embodied impacts have had sufficient time to be offset by accumulated operational savings.

Figure 6 synthesises Table 10 as a slopegraph of horizon-specific ranks (1 = lowest PLC(H)). Rankings shift markedly with the time horizon: in 2030, scenarios with low-upfront impacts are favoured, whereas by 2035—and especially by 2050—the leading options are those that minimise operational emissions. The figure highlights the transition from Kit 1 as the best-performing option in 2030 to S5 as the top-ranked pathway in 2035 and 2050, while S2 and Kit 5 improve substantially in the long horizon due to their much lower accumulated operational CO₂ emissions (B6).

Figure 7 complements the ranking view by reporting the magnitude of cumulative emissions avoided (labels on positive bars). It shows that several scenarios remain net-negative at the 2030 milestone (and some still at 2035), whereas by 2050, deep-decarbonisation pathways deliver substantially larger cumulative savings. Numbers above positive bars report the embodied-carbon efficiency indicator, ECI(H), revealing how much upfront impact is required per unit of cumulative benefit at each milestone (lower is better). Because avoided emissions are still limited in the short horizon, ECI values in 2030 and 2035 can become large when benefits are small, whereas long-horizon values provide a more stable basis for comparison. In 2050, the lowest GWP(A1–A3) per tCO₂e avoided values are obtained by Kit 1 and, among conventional measures, S3 and S4, indicating high

cumulative savings per unit of upfront impact. In contrast, highly integrated options such as Kit 4 and Kit 5—and to a lesser extent Kit 2—require close to one tonne of upfront GWP(A1–A3) per tonne avoided by 2050, reflecting a much higher embodied ‘investment’ for the long-term benefit. Deep-decarbonisation pathways such as S5 and S2 combine large long-term savings with moderate upfront efficiency, consistent with their strong 2050 performance.

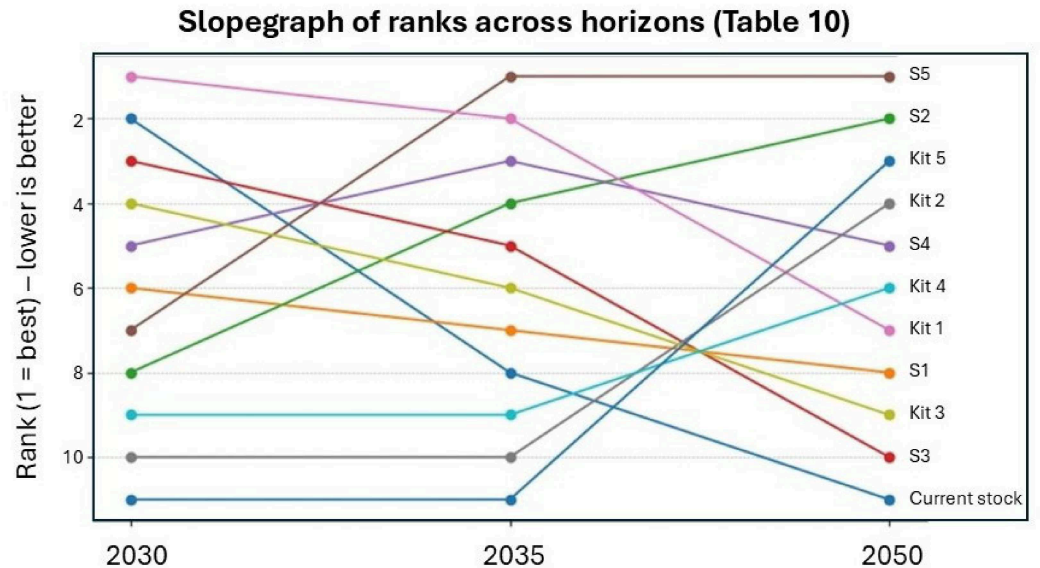


Figure 6. Horizon-specific ranking changes of renovation scenarios based on Table 10. Lines show scenario ranks (1 = lowest PLC(H)) across 2030, 2035 and 2050.

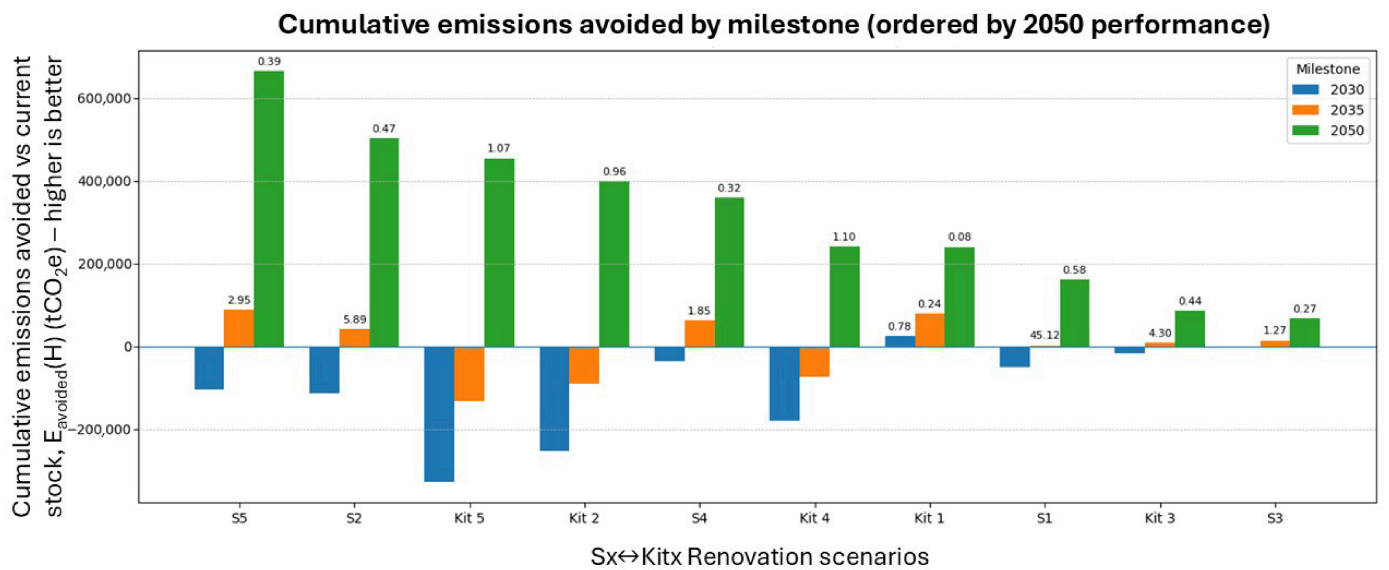


Figure 7. Cumulative emissions avoided relative to the current stock, $E_{\text{avoided}}(H)$, by 2030, 2035 and 2050, ordered by 2050 performance. Positive values indicate net cumulative savings by the corresponding milestone, whereas negative values indicate that upfront GWP(A1–A3) impacts have not yet been compensated within the assessed boundary. Numbers above positive bars are $ECI(H) = GWP(A1-A3)/E_{\text{avoided}}(H)(tCO_2e/tCO_2e)$. Note that the renovation scenarios are paired but not perfectly equivalent.

Importantly, values above the current stock benchmark at 2030 do not imply worse annual operation, but rather insufficient time to offset the upfront ‘carbon investment’ embedded in GWP (A1–A3) within this short horizon. At the 2030 horizon, only Kit 1 performs better than the current stock, reducing PLC(H), while all other scenarios remain

above the current stock value. Quantitatively, Kit 1 achieves a -15.5% reduction in PLC(H) relative to the current stock by 2030. This indicates that, within four years, operational savings are generally insufficient to compensate for the upfront GWP (A1–A3) burden for most interventions.

By 2035, the separation between scenarios becomes clearer, and several options perform better than the current stock. The lowest cumulative values are obtained by deep-decarbonisation packages (led by S5 and S4) and by a low-upfront high-performing option (Kit 1), followed by S2. By 2035, the best-performing option (S5) reduces PLC(H) by -24.8% relative to the current stock. In contrast, scenarios with higher upfront impacts and/or weaker operational decarbonisation remain above the current stock at this horizon, notably Kit 2, Kit 4, and Kit 5.

By 2050, differences further increase and deep operational decarbonisation dominates cumulative outcomes. S5 remains the lowest option, followed by S2 and the most ambitious industrialised package, Kit 5; the next-best options are Kit 2 and S4, while the remaining scenarios rank higher due to either residual operational emissions and/or higher upfront impacts. By 2050, S5 delivers a -70.7% reduction in PLC(H) relative to the current stock. Notably, Kit 5 remains almost time-invariant across horizons, consistent with near-zero operational emissions and a total dominated by upfront GWP (A1–A3). These outcomes are sensitive to assumptions affecting operational CO₂, particularly electricity-emission factors; this sensitivity is examined explicitly in Appendix B through bounded alternative electricity-decarbonisation cases. In addition, because the reported embodied boundary is limited to A1–A3, the ranking interpretation may also be affected by plausible downstream embodied burdens associated with A4–A5 and replacement-heavy components. This issue is examined through a bounded indicative sensitivity in Appendix C.

3.3. RQ3—Stock-Level Implications for Prioritisation and Sequencing

From a stock-management perspective, the results support prioritisation and sequencing rather than a single universally optimal package.

Table 11 reports baseline EP_{nren} by typology and climate cluster. It shows that baseline EP_{nren} is concentrated in specific typology segments, notably AB.03 in climate cluster B, which therefore emerges as the priority segment for portfolio-level intervention. In this study, this “worst-performing” designation refers to the largest contribution to stock-level EP_{nren} in absolute terms (MWh/y), rather than to the highest EP_{nren} intensity per m² and thus reflects both the size of the segment within the portfolio and its modelled energy performance. In addition, the horizon-based results show that the relative performance of the assessed pathways changes across 2030, 2035 and 2050, indicating that no single renovation package is uniformly preferable across all decision horizons.

Table 11. Non-renewable primary energy consumption (EP_{nren}) per building typology (MWh/y) of the current building stock ¹.

Climate Cluster	SFH.01	SFH.02	SFH.03	SFH.04	AB.01	AB.02	AB.03	AB.04
B	31	6195	3421	1381	316	25,384	63,484	49,715
C		8191	5197	3576		4158	16,202	24,627

¹ Empty cells indicate that there are no buildings of the specified type.

4. Discussion

4.1. Sustainability Trade-Off Between Operational Decarbonisation and Upfront Embodied Carbon

The results reveal a clear sustainability trade-off between upfront product-stage embodied carbon (GWP A1–A3) and operational decarbonisation (operational CO₂). This is

shown in Figure 4, where solutions that minimise operational CO₂—typically through electrification and PV—may carry a higher upfront GWP (A1–A3) footprint due to additional components and integration. Conversely, low GWP (A1–A3) options generally remain at more moderate operational CO₂ levels. Expressing this trade-off directly in CO₂e terms (operational CO₂ versus embodied GWP) is particularly informative in contexts where electrification and PV change the relationship between demand and emissions. Importantly, this trade-off should not be interpreted as an intrinsic “advantage” or “disadvantage” of industrialisation, but as a configuration-dependent balance between impacts that occur at different timescales: GWP (A1–A3) is incurred immediately, whereas operational savings accrue annually. From a sustainability perspective, this means that operational decarbonisation cannot be treated independently from the material and component burden required to achieve it.

4.2. Time Horizon as a Sustainability Decision Variable

Figure 5 provides a complementary synthesis of the operational-embodied trade-off by integrating annual operational CO₂ emissions, GWP (A1–A3), and carbon payback. In practice, Figure 4 shows whether a solution front-loads embodied emissions in exchange for lower operational CO₂, while carbon payback translates this balance into a time-to-compensation metric. The results indicate that options combining relatively low GWP (A1–A3) with meaningful annual B6 savings deliver earlier climate returns, whereas highly integrated solutions with near-zero operational CO₂ but large upfront burdens require longer horizons to become net-beneficial. This contrast is visible in Table 9 and Figure 5: Kit 1 achieves the shortest payback (1.8 years), whereas Kit 2 and Kit 5 require 11.8 and 12.4 years, respectively, due to their much larger upfront GWP (A1–A3) burdens.

The time-horizon results in Table 10 and Figures 6 and 7 reinforce this interpretation across milestones. Figure 6 summarises Table 10 as horizon-specific ranks (1 = lowest PLC(H)), highlighting how preferred options change across 2030, 2035 and 2050. Figure 7 adds a magnitude perspective by reporting cumulative emissions avoided, $E_{\text{avoided}}(H)$, and the embodied-carbon efficiency indicator, ECI(H), showing how carbon efficiency can vary at short horizons when avoided emissions are still limited, while long-horizon values provide a more stable basis for comparison. Taken together, these results show that time horizon is not simply a reporting choice, but a sustainability decision variable, because the relative merit of each pathway depends on how long annual operational savings are allowed to compensate the initial embodied “carbon investment”.

At the 2030 horizon, only Kit 1 yields a lower cumulative PLC(H) than the current stock, indicating that low-upfront interventions can deliver early climate returns. Most other scenarios remain above the current stock value in 2030, meaning that their initial embodied footprint is not yet compensated within this short period. By 2035, several options already outperform the current stock, with the lowest cumulative values obtained by deep-decarbonisation packages led by S5, followed by Kit 1, S4 and then S2. However, highly integrated kits with higher upfront burdens remain above the current stock at this milestone (Kit 2, Kit 4 and Kit 5), illustrating that the time required to compensate front-loaded GWP (A1–A3) emissions can extend beyond the 2035 horizon for some configurations.

By 2050, the ranking shifts further as cumulative operational decarbonisation dominates: S5 achieves the lowest cumulative climate impact, followed by S2 and the most ambitious industrialised option, Kit 5. A particularly informative pattern is the near-constant total of Kit 5 across horizons, indicating that once operational emissions approach near-zero, cumulative totals become dominated by the upfront GWP (A1–A3) term. This has a clear sustainable design implication: for near-zero operational solutions, further climate optimisation must increasingly target upfront impacts—material efficiency, minimi-

sation of integration substructures, and improved component strategies—because marginal improvements in operational CO₂ emissions (B6) become limited.

Overall, the horizon-based results confirm that the preferred renovation pathway changes materially with the decision timeframe: short horizons favour low-upfront pathways that deliver earlier benefits, whereas long horizons favour deeper decarbonisation packages whose cumulative operational savings eventually dominate within the adopted A1–A3 + B6 boundary. Appendix B shows that this horizon dependence is materially affected by lower electricity-emission factors, especially for highly electrified pathways, although the strongest long-horizon pathways remain robust across the tested cases. Appendix C further shows that the horizon-based interpretation is also sensitive to the embodied assessment boundary itself. When simple indicative burdens are added for A4–A5 and replacement-heavy components, ranking changes remain limited for low-equipment pathways but become more visible for highly integrated and equipment-heavy solutions. This reinforces that long-horizon conclusions should be interpreted primarily within the adopted A1–A3 + B6 boundary, with greater caution for technically intensive pathways.

4.3. What Industrialisation Changes Under Partial Comparability: Interpreting the Pairwise Comparisons (Sx vs. Kitx)

Pairwise comparisons (Sx vs. Kitx) remain useful for interpreting how industrialised solutions differ from their closest conventional counterparts, but they should be read with explicit reference to the comparability limits defined in Section 2.4.3. In the tighter pairings, especially S1 ↔ Kit 1 and, to a lesser extent, S3 ↔ Kit 3, the comparison is more robust. S1 ↔ Kit 1 illustrates the clearest case in which industrialisation shifts performance favourably within the assessed boundary: Kit 1 achieves broadly similar operational CO₂ to S1 while substantially reducing GWP (A1–A3), and it also exhibits the shortest payback. This supports the interpretation that industrialised envelope solutions can deliver clear climate benefits when material efficiency and systems simplicity are preserved.

For higher-integration packages, the interpretation must be more cautious. Kit 2 improves operational CO₂ relative to S2 but also increases GWP (A1–A3) substantially (Δ GWP (A1–A3) vs. paired S2 = −63%, i.e., ~63% higher GWP (A1–A3) than S2), resulting in a long payback (11.8 years) and weaker mid-term cumulative performance. Kit 5 similarly drives operational CO₂ towards near-zero, but its very high GWP (A1–A3) implies a long payback (12.4 years), meaning that its cumulative performance remains strongly shaped by the upfront embodied term throughout much of the assessed period. For S4 vs. Kit 4 and S5 vs. Kit 5, strict equivalence is reduced because the conventional scenarios include rooftop PV only, whereas the kits integrate PV on both roof and façade. The contrast is therefore best interpreted as one between alternative PV integration strategies, in which the façade-integrated option is associated with only a modest operational improvement, but also with substantially higher upfront GWP (A1–A3) and a much longer payback.

Overall, the pairwise results show that industrialisation does not automatically translate into lower product-stage embodied carbon: performance is configuration-dependent and driven by material quantities and the level of systems/PV integration. For that reason, industrialised kits should not be ranked on a single indicator or interpreted through a generic “industrialised versus conventional” lens, but assessed jointly through the operational-embodied trade-off (Figure 4) and the time-based metrics (Figures 5–7; Table 10), reported in this study.

4.4. Sustainable Portfolio-Level Planning and Sequencing in Public Housing

From a public-housing stock perspective, the results support a portfolio logic rather than a single optimum package. Table 11 indicates that a substantial share of baseline EPnren is concentrated in specific typologies (notably AB.03 in cluster B), suggesting that

prioritising interventions in those segments can deliver larger stock-average reductions. In this study, this “worst-performing” designation refers to the typology segment with the largest contribution to stock-level EP_{nren} (MWh/y), rather than to the highest EP_{nren} intensity per m², and therefore directly supports portfolio prioritisation across the assessed stock.

At the same time, the combined evidence from Figures 4–6 and Table 10 shows that “best” options depend on the decision horizon: low-upfront, fast-payback measures deliver early net climate benefits, while deep-decarbonisation packages dominate cumulative outcomes over longer horizons. This means that stock-level sustainable renovation planning cannot rely on operational metrics alone, nor on a single endpoint ranking. Rather, it must consider how embodied carbon, operational decarbonisation and time horizon interact when interventions are prioritised across heterogeneous building segments.

A practical sequencing implication follows: Scalable, low-upfront and fast-payback measures (e.g., Kit 1) can be rolled out widely to improve a large share of the stock within short horizons, while deeper, higher-integration packages should be deployed more selectively, in those priority segments where long service life, stronger long-term cumulative savings and programme-level strategic value justify higher upfront impacts. In this sense, the results support a sustainability-oriented sequencing logic based on both typology prioritisation and horizon-dependent climate performance, rather than on the assumption that a single renovation package is optimal for all buildings and all decision horizons.

4.5. Policy Relevance Under the Adopted Partial Boundary

The findings have direct relevance for stock-level renovation planning in the context of EPBD-driven trajectories. Even without assuming a specific annual renovation rate, the short-horizon evidence (Table 10) indicates that interventions with low-upfront impacts and short payback (e.g., Kit 1) are more aligned with near-term climate milestones, because they can reduce cumulative PLC(H) within a relatively limited timeframe. By contrast, the long-horizon evidence shows that deep operational decarbonisation packages (e.g., S5, and among kits Kit 5) dominate cumulative outcomes by 2050 when long service life can be ensured. In this sense, the results highlight that the timing of climate benefits matters for policy interpretation, and that pathway selection depends not only on the magnitude of operational savings, but also on the pace at which those savings compensate the initial embodied burden.

More broadly, the results reinforce that policy-relevant stock-level renovation assessment requires more than operational performance metrics alone. If renovation programmes prioritise measures only on the basis of B6 reductions, they risk shifting part of the climate burden upstream into product-stage embodied impacts, GWP (A1–A3). By contrast, combining GWP (A1–A3), operational CO₂, and horizon-based indicators enables a more transparent interpretation of climate performance across competing renovation pathways. This is particularly important in public housing, where decision makers must balance climate mitigation, resource use, scalability, and implementation feasibility across a large and diverse building stock. These implications should nevertheless be interpreted within the adopted partial boundary of the study.

4.6. Limitations and Sensitivity Needs

Several limitations should be acknowledged. First, embodied carbon is represented by A1–A3, which supports comparability across alternatives, but it may not capture stages where industrialised renovation could provide additional advantages, such as reduced on-site waste and rework (A5), different logistics (A4), changes in replacement cycles

(B4–B5), and end-of-life pathways (C/D). This is especially relevant for integrated packages that include equipment (heat pumps, ventilation units, PV inverters) and PV integration strategies, where replacements and end-of-life may influence long-horizon outcomes. In addition, the exclusion of A4–A5 may affect relative rankings, since industrialised solutions may reduce on-site waste and rework while also showing different transport requirements. Any statements about longer-term performance are therefore limited to the adopted partial indicators combining GWP (A1–A3) with operational emissions (B6) over the assessed horizons. To partially address this limitation without implying a full EN 15978 whole-life assessment, Appendix C provides a bounded indicative sensitivity for A4–A5 and replacement-heavy components. The appendix shows that the comparative interpretation of low-equipment pathways remains broadly stable, whereas more integrated equipment-heavy pathways are more sensitive to boundary extension.

Second, operational results depend on modelling assumptions. CERMA provides a consistent and certification-oriented framework for stock-level comparison, but some INFINITE technologies are represented through equivalent modelling constructs, and certain phenomena cannot be modelled explicitly, such as evapotranspiration or opaque-façade shading effects. In addition, the embodied-carbon comparison combines kit-specific information from developers/manufacturers with BDC/TURIA-based datasets for conventional measures. This mixed-data approach improves representativeness and preserves internal consistency for comparative interpretation, but it may affect absolute values and therefore calls for caution when reading small pairwise differences as precise equivalences. These limitations are particularly relevant in the partially matched scenario pairs discussed in Sections 3 and 4.

Third, horizon-based results are sensitive to assumptions affecting operational CO₂, especially those related to electricity. EP_{nren} and operational CO₂ are computed using scenario-invariant CTE/CERMA conversion factors applied consistently across all options; accordingly, the analysis does not model future changes in grid-emission intensity. This matters because future electricity decarbonisation would reduce operational CO₂ intensity and could lengthen carbon payback periods, particularly for options whose climate benefits rely strongly on operational emissions reductions. Appendix B addresses one key part of this uncertainty through a bounded electricity-decarbonisation sensitivity. The results show that lower electricity-emission factors systematically lengthen carbon payback times and reduce the relative advantage of highly electrified pathways at short and intermediate horizons. Under the moderate decarbonisation case, S5 remains the best-performing pathway in 2050, followed by S2, but Kit 2 overtakes Kit 5. Under the strong decarbonisation case, no renovation scenario outperforms the current stock by 2030, and the current stock remains the lowest-PLC(H) case in 2035; however, S5 and S2 remain the strongest long-horizon pathways by 2050. The present results should therefore be interpreted as comparative outcomes under a transparent and internally consistent set of current factors, rather than as forecasts of future policy or technological conditions.

Taken together, these limitations do not invalidate the comparative contribution of the study, but they do define the scope within which its conclusions should be interpreted. The results robustly show how embodied carbon, operational decarbonisation and decision horizon interact at stock level under the adopted A1–A3 + B6 boundary; however, they also show that boundary-related assumptions remain relevant, as illustrated by the bounded indicative sensitivity in Appendix C. Clear priorities for future work therefore include fuller modelling of A4–A5 and replacement-heavy components, more explicit uncertainty treatment for kit-specific modelling approximations, and alternative electricity-emission-factor scenarios for long-horizon interpretation.

5. Conclusions

This study evaluated the portfolio-scale impacts of industrialised and conventional renovation pathways for a public residential building stock by combining operational performance (B6) with product-stage embodied carbon reported as GWP (A1–A3). Within the adopted partial boundary, the results show a clear sustainability trade-off: pathways that achieve stronger operational decarbonisation often require higher upfront embodied impacts, and these two dimensions cannot be interpreted independently.

The results also show that preferred renovation pathways change materially with the decision horizon. At short horizons, low-upfront options deliver earlier cumulative climate benefits, whereas at longer horizons, deeper decarbonisation packages achieve lower cumulative PLC(H) values as operational savings accumulate. Within the assessed boundary, Kit 1 emerges as the strongest short-horizon option because of its low-upfront burden and rapid carbon payback, while S5 provides the strongest long-horizon cumulative performance by 2050.

The pairwise comparisons further indicate that industrialisation does not systematically reduce product-stage embodied carbon. Within the reported A1–A3 boundary, Kit 1 is the only industrialised option that reduces GWP (A1–A3) relative to its paired conventional counterpart, whereas higher-integration kits increase upfront impacts and therefore front-load a larger share of the climate burden. These pairwise contrasts should nevertheless be interpreted cautiously where strict one-to-one functional equivalence is limited, particularly in the S2 ↔ Kit 2, S4 ↔ Kit 4 and S5 ↔ Kit 5 comparisons.

The bounded sensitivities reported in Appendices B and C further qualify the long-horizon interpretation. Appendix B shows that lower electricity-emission factors reduce the relative advantage of highly electrified pathways at short and intermediate horizons, even if the strongest 2050 pathways remain broadly robust across the tested cases. Appendix C shows that extending the embodied interpretation beyond A1–A3 through indicative A4–A5 and replacement-heavy burdens is unlikely to alter the broad reading of low-equipment pathways, but may affect the relative position of highly integrated and equipment-intensive solutions. The main findings should therefore be interpreted as robust primarily within the adopted A1–A3 + B6 boundary.

From a public-housing stock perspective, the findings support a portfolio logic rather than a single optimum package. Scalable, fast-payback measures can be deployed broadly to raise the performance floor of the stock and deliver earlier net climate benefits, while deeper and more highly integrated retrofits should be deployed more selectively in priority segments where longer service life and stronger long-term cumulative savings justify higher upfront impacts. In this sense, sustainable stock-level renovation planning is best understood as a sequencing problem that must jointly consider embodied carbon, operational decarbonisation, and time horizon within the adopted partial boundary.

Future work should extend the system boundary beyond the current screening scope to include A4–A5 and additional life-cycle modules such as B4–B5, C and optional D, and should further test sensitivities related to replacement cycles, PV performance, and alternative electricity-decarbonisation trajectories. This would support a fuller whole-life carbon appraisal and strengthen comparative interpretation beyond product-stage reporting.

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Abbreviations

The following abbreviations are used in this manuscript:

AB	Apartment Blocks
BIPV	Building-integrated PV
DHW	Domestic Hot Water
ECI	Embodied Carbon efficiency indicator
EPBD	Energy Performance of Buildings Directive
EPnren	Non-renewable Primary Energy consumption
EU	European Union
GWP	Global Warming Potential
H	Horizon
HVAC	Heating, Ventilation and Air Conditioning
LCA	Life Cycle Assessment
MVHR	Mechanical Ventilation with Heat Recovery
PLC(H)	Partial Life-cycle Climate indicator at a given horizon H
PV	Photovoltaic
RQ	Research Question
SFH	Single Family Houses

Appendix A

Table A1. Renovation scenarios (I: Industrialised; C: Conventional; (i) envelope-only upgrades; (ii) deep retrofit; (iii) integration of on-site renewable electricity generation).

Scenario	Approach	Level	Description	Opaque Envelope (Façade/Roof/Party Walls *)	Windows & Solar Control	Heating–Cooling–DHW System	Mechanical Ventilation	PV Integration
Kit 1	I	(i)	Passive eco-compatible & green envelope kit	Insulation of opaque envelope with vegetal finishes	-	-	-	-
S1	C	(i)	Envelope insulation	Insulation of opaque envelope	-	-	-	-
Kit 2	I	(ii)	Energy and fresh air distribution kit	Insulation of opaque envelope	Window replacement	Air-source heat pump (H/C/DHW)	Façade-integrated mechanical ventilation with heat recovery *	-

Table A1. Cont.

Scenario	Approach	Level	Description	Opaque Envelope (Façade/Roof/Party Walls *)	Windows & Solar Control	Heating–Cooling–DHW System	Mechanical Ventilation	PV Integration
S2	C	(ii)	Envelope insulation, windows & air-source heat pump	Insulation of opaque envelope	Window replacement	Air-source heat pump (H/C/DHW)	- *	-
Kit 3	I	(i)	Smart window kit	-	Window replacement with dynamic shading	-	-	-
S3	C	(i)	Windows	-	Window replacement	-	-	-
Kit 4	I	(iii)	BIPV kit	Insulation of opaque envelope	-	-	-	Roof + Façade *
S4	C	(iii)	Envelope insulation & PV	Insulation of opaque envelope	-	-	-	Roof*
Kit 5	I	(iii)	Integrated kit	Insulation of opaque envelope with vegetal finishes	Window replacement with dynamic shading	Air-source heat pump (H/C/DHW)	Façade-integrated mechanical ventilation with heat recovery *	Roof + Façade *
S5	C	(iii)	Envelope insulation, windows, air-source heat pump & PV	Insulation of opaque envelope	-	Air-source heat pump (H/C/DHW)	Baseline (no MVHR) *	Roof *

* Differences between the corresponding pairs.

Appendix B. Electricity-Decarbonisation Sensitivity

Appendix B.1. Sensitivity Setup

To test the sensitivity of long-horizon results to electricity-related assumptions, an additional bounded sensitivity analysis was performed by recalculating annual operational CO₂ emissions (B6), carbon payback, and the partial life-cycle climate indicator, PLC(H), under alternative electricity-emission-factor cases. The reference case retained the current CERMA/CTE electricity-emission factor for grid electricity (0.331 kgCO₂/kWh final), while two lower-emission cases were introduced to represent moderate and strong electricity decarbonisation. Natural-gas factors were kept unchanged. This sensitivity is not intended as a forecast of future grid conditions, but as a bounded test of how the relative performance of the assessed renovation pathways changes when the carbon intensity of electricity decreases. Consistent with the main study, GWP(A1–A3) values were kept unchanged, and the same time horizons were used (2030, 2035 and 2050).

Table A2. Electricity-emission-factor cases used in the sensitivity analysis.

Case	Description	Electricity-Emission Factor (kgCO ₂ /kWh Final)
Case 0	Current/fixed factor	0.331
Case 1	Moderate decarbonisation	0.200
Case 2	Strong decarbonisation	0.05

Note: Natural-gas factors were kept unchanged at the value used in the main study.

Appendix B.2. Recalculated Annual Operational CO₂ and Carbon Payback

Operational CO₂ emissions were recalculated from the carrier-disaggregated operational CO₂ values used as input to this sensitivity. The electricity-related term was rescaled according to the ratio between the new electricity-emission factor and the current/fixed fac-

tor, while the natural-gas term was kept unchanged. Carbon payback was then recalculated using the same definition adopted in the main text.

Table A3. Recalculated annual operational CO₂ emissions (B6) and carbon payback under alternative electricity-emission-factor cases.

Scenario	B6 Current Factor (tCO ₂ /y)	B6 Moderate Decarb.	B6 Strong Decarb.	Payback Current * (y)	Payback Moderate (y)	Payback Strong (y)	Scenario
Current stock	39,108.89	29,951.46	19,465.86	—	—	—	Current stock
S1	28,521.27	23,554.11	17,866.52	8.81	14.59	58.35	S1
S2	8377.82	5062.13	1265.53	7.70	9.50	12.99	S2
S3	35,624.81	27,846.28	18,939.56	5.04	8.35	33.39	S3
S4	19,397.84	18,041.46	16,488.36	5.84	9.67	38.68	S4
S5	700.79	423.44	105.86	6.73	8.75	13.34	S5
Kit 1	28,334.46	23,441.23	17,838.30	1.75	2.90	11.61	Kit 1
Kit 2	6445.43	3894.52	973.63	11.78	14.76	20.80	Kit 2
Kit 3	33,967.84	26,845.09	18,689.27	7.32	12.12	48.48	Kit 3
Kit 4	18,101.59	17,258.23	16,292.55	12.58	20.83	83.31	Kit 4
Kit 5	1.08	0.65	0.16	12.40	16.20	24.92	Kit 5

* “Current factor” values in this appendix are reconstructed from the carrier-disaggregated operational CO₂ data used for the sensitivity analysis and may therefore differ slightly from the published totals in Table 9 because of rounding or export precision. The main-text tables remain the reference for the base case.

Appendix B.3. Recalculated PLC(H) Under Alternative Electricity-Emission-Factor Cases

Using the same formulation adopted in the main text, PLC(H) was recalculated by keeping GWP(A1–A3) unchanged and accumulating the recalculated B6 values across the same horizons: H = 4 years (2030), H = 9 years (2035), and H = 24 years (2050).

Table A4. Recalculated PLC(H) under the moderate electricity-decarbonisation case (tCO₂e).

Scenario	2030 (H = 4)	2035 (H = 9)	2050 (H = 24)
Current stock	119,805.85	269,563.17	718,835.11
S1	187,534.44	305,304.99	658,616.64
S2	256,757.51	282,068.14	358,000.05
S3	128,958.12	268,189.51	685,883.70
S4	187,325.85	277,533.17	548,155.13
S5	260,044.75	262,161.94	268,513.51
Kit 1	112,657.94	229,864.11	581,482.62
Kit 2	400,265.08	419,737.68	478,155.47
Kit 3	145,031.36	279,256.80	681,933.14
Kit 4	333,408.92	419,700.08	678,573.54
Kit 5	485,093.61	485,096.87	485,106.66

Table A5. Recalculated PLC(H) under the strong electricity-decarbonisation case (tCO₂e).

Scenario	2030 (H = 4)	2035 (H = 9)	2050 (H = 24)
Current stock	77,863.44	175,192.74	467,180.64
S1	164,784.09	254,116.70	522,114.54
S2	241,571.13	247,898.79	266,881.76
S3	93,331.26	188,029.08	472,122.56
S4	181,113.44	263,555.25	510,880.66
S5	258,774.44	259,303.74	260,891.63
Kit 1	90,246.21	179,437.73	447,012.28
Kit 2	388,581.52	393,449.67	408,054.12
Kit 3	112,408.07	205,854.41	486,193.41
Kit 4	329,546.21	411,008.97	655,397.27
Kit 5	485,091.65	485,092.47	485,094.92

Appendix B.4. Ranking Changes Under Electricity Decarbonisation

To facilitate comparison with the horizon-specific rank changes already reported in the main text, Figure A1 reproduces the slopegraph logic of Figure 6 under the three electricity-emission-factor cases. Rather than repeating the rank information in tabular form, the

figure provides a direct visual comparison of how lower electricity-emission factors modify the relative position of the assessed pathways across the 2030, 2035 and 2050 horizons.

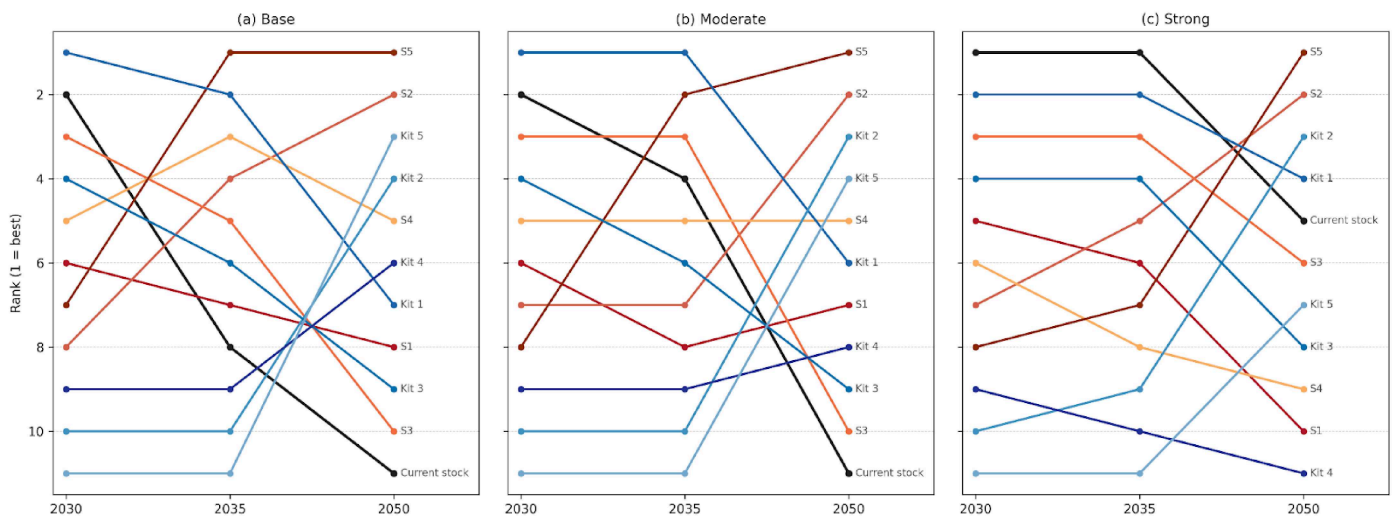


Figure A1. Horizon-specific ranking of renovation scenarios under the base case and the electricity-decarbonisation sensitivity cases. Panels show scenario ranks (1 = lowest PLC(H)) across 2030, 2035 and 2050 for (a) the base case using the current/fixed electricity-emission factor, (b) the moderate decarbonisation case, and (c) the strong decarbonisation case.

Figure A1 complements the recalculated PLC(H) values reported above by showing how lower electricity-emission factors affect the rank trajectory of the assessed pathways. The base case reproduces the main-text pattern, with Kit 1 as the best-performing pathway at 2030 and S5 as the best-performing pathway in 2035 and 2050, consistent with the original horizon-based interpretation of the study. Under the moderate decarbonisation case, Kit 1 remains the top option in 2030 and becomes the best option at 2035, while S5 remains the best-performing pathway in 2050. Under the strong decarbonisation case, the current stock remains the lowest-PLC(H) case at 2030 and 2035, reflecting the reduced annual CO₂ savings available to compensate the upfront GWP (A1–A3) burden when electricity becomes much less carbon-intensive. By 2050, however, S5 and S2 remain the strongest pathways, although the relative position of several electrified industrialised options changes materially. This confirms that long-horizon rankings are sensitive to electricity-related assumptions, particularly for highly electrified pathways, even if the strongest 2050 pathways remain broadly robust across the tested cases.

Appendix B.5. Interpretation of the Electricity-Decarbonisation Sensitivity

The sensitivity shows that lower electricity-emission factors systematically reduce annual operational CO₂ across all scenarios with grid-electricity demand, but they also reduce annual CO₂ savings relative to the current stock, thereby lengthening carbon pay-back times. This effect is especially relevant for highly electrified pathways. Under the moderate decarbonisation case, only Kit 1 still outperforms the current stock by 2030, while by 2035 Kit 1 becomes the best-performing pathway, followed by S5 and S3. By 2050, S5 remains the best-performing pathway, followed by S2, but Kit 2 overtakes Kit 5. Under the strong decarbonisation case, no renovation scenario performs better than the current stock by 2030, and the current stock remains the lowest-PLC(H) case in 2035; however, S5 and S2 remain the strongest long-horizon pathways by 2050, followed by Kit 2. These results confirm that long-horizon conclusions are sensitive to electricity-related assumptions and that the relative position of highly electrified pathways becomes less favourable under lower grid-emission factors, especially at short and intermediate horizons.

Appendix C. Indicative Bounded Sensitivity for A4–A5 and Replacement-Heavy Components

To strengthen the interpretation of the long-horizon results within the adopted partial boundary, an indicative bounded sensitivity analysis was performed for modules A4–A5 and, where relevant, replacement-heavy components. This appendix is not intended as a full EN 15978 whole-life carbon assessment. Rather, it provides a simple scenario-bounded test of whether plausible downstream additions could materially affect the comparative interpretation of the reported A1–A3 + B6 results.

Three scenario groups were defined according to the degree of technical integration represented by the assessed renovation pathways. A first group comprises low-equipment pathways, dominated by envelope or window interventions with limited technical-system content (S1, S3, Kit 1, Kit 3). A second group comprises medium-equipment pathways, including heat pumps, mechanical ventilation with heat recovery, or PV/BIPV-related components (S2, S4, Kit 2, Kit 4). A third group comprises highly integrated equipment-heavy pathways combining envelope, systems and on-site renewables within a single package (S5, Kit 5). This grouping follows the scenario definitions and the matched/unmatched scope discussion presented in Sections 2.4.2 and 2.4.3 and Appendix A. These scenario distinctions are consistent with the scope differences already described in the manuscript, especially for MVHR and PV/BIPV integration.

Because project-specific information on transport routes, site access, installation logistics, construction-stage waste, and component replacement schedules was not available at the stock level, A4–A5 and replacement effects were not modelled deterministically. Instead, they were represented as additional burdens expressed as percentages of the reported GWP (A1–A3). This approach is consistent with the purpose of this appendix, which is to provide a bounded robustness test rather than a full whole-life calculation. It is also aligned with the scope limitation explicitly stated in the main methodology, where construction-stage modules and replacement-related effects are outside the embodied-carbon reporting boundary.

For the central sensitivity case, the following assumptions were adopted. Low-equipment pathways were assigned an additional burden equal to 10% of reported GWP (A1–A3), combining a modest A4–A5 contribution and a limited replacement contribution. Medium-equipment pathways were assigned an additional burden of 30% of reported GWP (A1–A3), reflecting a higher likelihood of transport- and installation-related impacts as well as replacement of technical equipment such as heat pumps, ventilation units, PV-related components or inverters. Highly integrated equipment-heavy pathways were assigned an additional burden of 40% of reported GWP (A1–A3), reflecting the combined presence of multiple technical systems and the greater relevance of replacement-boundary effects in long-horizon interpretation. These assumptions are not intended to represent measured programme-specific values, but rather an intermediate bounded case designed to test the robustness of the comparative interpretation.

Accordingly, the adjusted partial life-cycle climate indicator was calculated as:

$$PLC_{adj}(H) = PLC(H) + GWP(A1 - A3) \times \delta$$

where $PLC(H)$ is the partial life-cycle climate indicator reported in the main text, $GWP(A1-A3)$ is the product-stage embodied carbon already reported for each scenario, and δ is the indicative additional burden assigned to the corresponding scenario group. Since the original $PLC(H)$ results are already reported for 2030, 2035 and 2050, this formulation allows the bounded effect of A4–A5 and replacement-heavy components to be examined without

recalculating operational emissions. Table A6 summarises the assumptions adopted in the bounded sensitivity analysis.

Table A6. Indicative bounded assumptions used for the additional sensitivity analysis.

Scenario Group	Scenarios Included	Central Additional Burden Applied to Reported GWP (A1–A3)
Low-equipment pathways	S1, S3, Kit 1, Kit 3	10%
Medium-equipment pathways	S2, S4, Kit 2, Kit 4	30%
Highly integrated equipment-heavy pathways	S5, Kit 5	40%

Using these assumptions, the adjusted values of the partial life-cycle climate indicator for 2035 and 2050 were recalculated as shown in Table A7.

Table A7. Adjusted PLC(H) values under the central bounded sensitivity case.

Scenario	GWP (A1–A3) (tCO ₂ e)	Applied Additional Burden	Added Burden (tCO ₂ e)	PLC(2030) Adjusted (tCO ₂ e)	PLC(2035) Adjusted (tCO ₂ e)	PLC(2050) Adjusted (tCO ₂ e)
S1	93,318	10%	9332	216,756	359,387	787,281
S2	236,509	30%	70,953	340,990	382,902	508,635
S3	17,573	10%	1757	161,854	340,009	874,473
S4	115,160	30%	34,548	227,336	324,371	615,476
S5	258,351	40%	103,340	364,500	368,012	378,548
Kit 1	18,893	10%	1889	134,119	275,792	700,809
Kit 2	384,687	30%	115,406	525,874	558,102	654,783
Kit 3	37,651	10%	3765	177,287	347,126	856,644
Kit 4	264,376	30%	79,313	416,095	506,603	778,127
Kit 5	485,091	40%	194,036	679,131	679,136	679,153

Figure A2 complements Table A7 by showing how the bounded extension of the assessment boundary affects the relative ranking of the assessed pathways. This visualisation is especially useful because the purpose of the appendix is not only to quantify added burdens, but also to test whether the comparative interpretation changes once indicative A4–A5 and replacement effects are included. The figure shows that ranking changes are limited for low-equipment pathways, whereas equipment-heavy and highly integrated pathways are more sensitive to boundary extension, particularly at the longer horizons where comparative interpretation is most policy-relevant.

Figure A2 compares the scenario ranking based on the reported partial life-cycle climate indicator, PLC(H), and the adjusted ranking obtained after adding the indicative bounded A4–A5 and replacement burdens defined in Appendix C. Rankings are shown for 2030, 2035 and 2050, with rank one indicating the lowest PLC(H). The figure highlights that low-equipment pathways remain comparatively stable, whereas equipment-heavy and highly integrated pathways are more sensitive to boundary extension, particularly at medium and long horizons.

The sensitivity results suggest that the comparative interpretation of low-equipment pathways is only marginally affected by the inclusion of indicative A4–A5 and replacement burdens. In particular, Kit 1 remains a robust low-upfront-carbon pathway with favourable short- and mid-horizon performance. By contrast, the medium- and high-equipment pathways are more sensitive to the boundary extension, especially those with higher reported GWP (A1–A3) and greater technical integration. This is particularly visible for Kit 2, Kit 4 and Kit 5, whose long-horizon performance becomes less favourable once bounded downstream additions are considered.

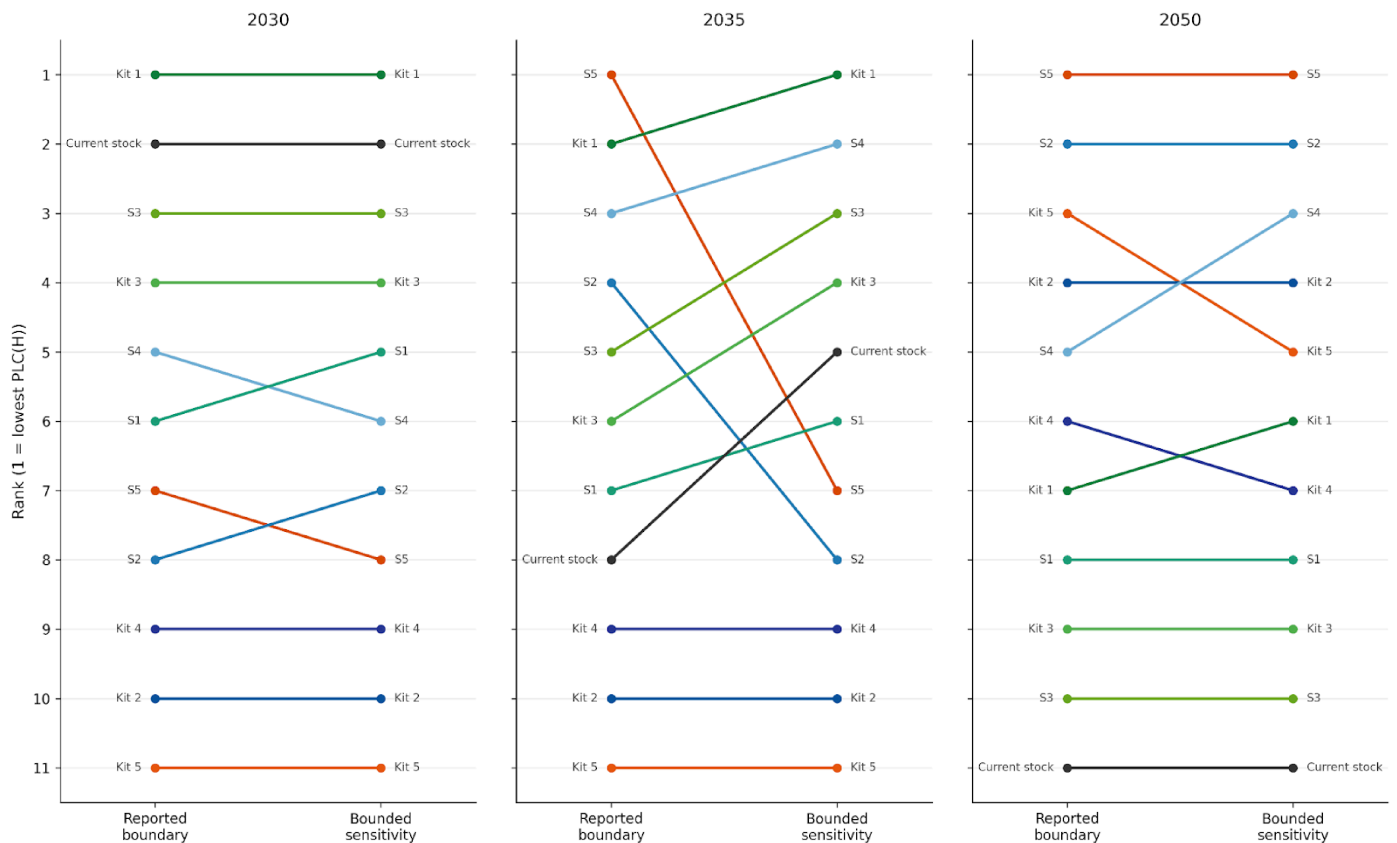


Figure A2. Effect of the bounded boundary extension on the relative ranking of assessed renovation pathways across the 2030, 2035, and 2050 horizons.

At the 2030 horizon, the inclusion of indicative downstream burdens further reinforces the importance of upfront impacts, because there is limited time for annual operational savings to compensate for the added embodied burden. Under this bounded sensitivity, low-equipment pathways remain the least affected, whereas highly integrated pathways move further away from the current stock benchmark. This supports the interpretation that short-horizon conclusions are especially sensitive to boundary extension when renovation options concentrate a large share of their climate burden upfront.

At the same time, the central bounded sensitivity does not overturn the main interpretation that deep-decarbonisation pathways may remain favourable at long horizons within the assessed stock. In particular, S5 remains the strongest 2050 pathway under the central sensitivity case, although with a higher cumulative value than under the reported A1–A3 + B6 boundary. This is consistent with the main-text finding that deeper decarbonisation packages perform more strongly at long horizons, while also reinforcing that their relative position should be interpreted more cautiously when equipment-heavy boundary effects are not explicitly modelled.

Overall, this appendix materially strengthens the interpretation of the manuscript by showing that the omission of A4–A5 and replacement effects is unlikely to alter the broad reading of low-equipment pathways, but may affect the relative ranking of equipment-heavy solutions. The main results should therefore be read as robust primarily within the adopted A1–A3 + B6 partial boundary, with additional caution required when interpreting highly integrated pathways over long horizons.

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