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Embodied carbon of Germany's residential stock and the emission cost of retrofitting it

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Article

Keywords:

Posted Date: October 27th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11289450/v1

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Embodied carbon of Germany's residential stock and the emission cost of retrofitting it

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Abstract

Carbon budgets and embodied carbon limits presuppose an account of what the existing building stock embodies and has yet to emit, but none exists at German national scale. Here we resolve all 19.4 million German residential buildings individually, estimating their embodied carbon emissions from real geometry and age-specific constructions over life-cycle phases A1–A3, B4 and C3–C4. Embodied carbon averages 6.3 kg CO_2e per square meter net floor area per year. Most of the stock's remaining embodied emissions are incurred at end of life rather than through component replacement, making lifetime extension the strongest embodied carbon lever. However, retrofitting it to an advanced standard at 2% of floor area per year would emit 287 to 559 Mt CO_2e depending on the materials used, which is 59 to 114% of the German building sector's embodied carbon budget for 2025–2045. Decarbonizing the existing stock must account for the carbon a retrofit costs.

Introduction

The materials embodied in a building are largely determined when it is built [1], but their carbon related consequences extend throughout its life cycle, from production to component replacement and disposal. Yet efforts to align the sector with climate limits have focused overwhelmingly on operational energy consumption[2]. As electricity grids decarbonize and building envelopes improve, embodied emissions account for an increasing share of whole-life emissions, from approximately 20–25% in buildings constructed to current standards to 45–50% in highly energy-efficient buildings[1]. Long overlooked in climate policy[3, 4], embodied carbon is receiving increasing attention, as emerging European regulation begins to constrain emissions from new construction.

Much of this attention focuses on the embodied carbon of new housing to meet growing housing demands. Recent analyses show that meeting housing needs would

substantially pressure carbon budgets [5–7]. Decarbonizing the existing housing stock through rapid energy retrofit has been proposed as part of the solution[5]. Yet retrofit itself has life-cycle consequences: high renovation rates can generate a near-term carbon spike from the embodied emissions of renovation materials[8], while European pathway modeling shows that future building-sector emissions depend on the timing and implementation of renovation alongside other mitigation strategies [9]. The existing stock is therefore not carbon-free to maintain or decarbonize. Component replacement and end of life treatment carry future embodied emissions, while retrofit introduces additional emissions that compete with new construction for the same shrinking carbon budget.

Germany faces the same challenge as other European countries: accelerating renovation to reduce operational emissions while keeping the embodied emissions it generates within said receding carbon budget. Achieving climate neutrality by 2045 requires rapid energy renovation[10, 11], yet German building-sector regulation has focused predominantly on operational energy[12, 13]. Embodied carbon is now entering this policy landscape through a proposed dynamic carbon budget for the German building sector [14] and life-cycle carbon requirements for new buildings under the recast European Energy Performance of Buildings Directive (EPBD)[15]. However, the future embodied emissions associated with maintaining and renovating the existing stock remain insufficiently quantified. A spatially explicit, building-level account is therefore needed to identify where these emissions will arise and assess whether alternative retrofit pathways can remain within the available carbon budget.

Here we provide precisely this account. To our knowledge, this is the first embodied carbon estimation of an entire national residential stock resolved to every individual building, computed from building-specific geometry instead of typological archetypes. Previous literature describes the built environment through material archetypes and spatial units, by material-flow analysis[16–19] or material-stock accounting[20–23]. Life-cycle assessment of building stocks reaches city and national scale[9, 24–26], but usually through typological archetypes, aggregated representations or case studies (Supplementary Table 18). These approaches cannot fully capture geometric variation among buildings of the same type or locate future embodied emissions in individual buildings. By resolving the standing stock building by building, our account captures this variation, reveals regional differences obscured by national aggregates [18, 19], and provides a basis for designing targeted retrofit pathways on any regional level.

Specifically, we combine geo-referenced geometric attributes for Germany's entire residential stock [27, 28] with ecological performance data for over 1,000 German building constructions[29] supplemented by typological references where needed [30, 31]. Using these, we compute embodied carbon aligned with DIN EN 15978, over life-cycle modules A1–A3, B4 and C3–C4, for each of Germany's 19.4 million residential buildings as built, at a resolution that aggregates to any spatial unit. Instead of replacing stock-level pathway models, this bottom-up estimation complements them by locating future embodied carbon liabilities in the buildings from which they arise. Stock assessments have traditionally faced a trade-off between model resolution and policy relevance[32]. By bridging this trade-off, our building-level approach allows alternative retrofit pathways to be constructed from individual buildings instead

of representations. In a second step, we therefore test how retrofit rate, building treatment order and material choice determine whether decarbonizing the standing stock can remain within the embodied carbon budget allocated to the German building sector for 2025–2045.

Results and discussion

Embodied carbon in Germany's residential buildings decreases with building compactness but increases in more recent construction

We estimated the embodied carbon of all 19.4 million German residential buildings, each from its own geometry and the documented constructions of its respective period, over life-cycle modules A1–A3, B4 and C3–C4 (Fig. 1). Median Global Warming Potential (GWP) is 7.2 $kg\,CO_2e/(m^2{\cdot}a)$ – per net floor area and annualized over a 50-year study period – with the middle 80% of buildings between 4.7 and 9.3 (Supplementary Table 12). Weighting each building by its net floor area gives a stock aggregate of 6.3 $kg\,CO_2e/(m^2{\cdot}a)$, below the median because larger buildings hold disproportionate floor area at lower GWP intensity. Because the exact construction of any individual building is unknown, each value is a representative estimate drawn from a pool of documented constructions for that building's age class and component, and the resulting bias is quantified in Supplementary Note 3.

Embodied carbon intensity falls monotonically across the four building typology categories (Fig. 2a). Terraced and single-family houses carry the highest medians, at 7.5 and 7.4 $kg\,CO_2e/(m^2{\cdot}a)$, multi-family houses fall to 6.2, and apartment buildings to 4.4 $kg\,CO_2e/(m^2{\cdot}a)$. A building's envelope of roof, external walls and windows accounts for 48% of intensity in single-family and terraced houses but only 30% in apartment buildings (Supplementary Fig. 3), because a larger building spreads this envelope over more floor area. Single-family and terraced houses are 85% of the stock (Supplementary Table 6), so the national median sits close to theirs. Housing types set the average and not the individual value[34], as the spread within each age class in Fig. 2a shows.

Even within each typology, embodied carbon intensity decreases with increasing building compactness, measured by ratio of net floor area to building footprint area. This relationship is illustrated for both single-family homes (Fig. 2c) and multi-family homes (Fig. 2d) in two age classes. The wide range of compactness within each group contributes to substantial differences in intensity. For example, embodied carbon intensities for single-family homes built between 2002 – 2009 (BAC9) span approximately 6 to 14 kg,$CO_2e/(m^2{\cdot}a)$ (Fig. 2c) and for multi-family homes approximately 4 to 14 kg,$CO_2e/(m^2{\cdot}a)$ (Fig. 2d). In addition to the net floor area to building footprint ratio, differences in other aspects of building geometry related to compactness, such as wall-to-floor area ratios and roof shapes, contribute to the spread in estimated embodied carbon intensity, reflected in the vertical width of the plotted distributions. This substantial within-group variation highlights the

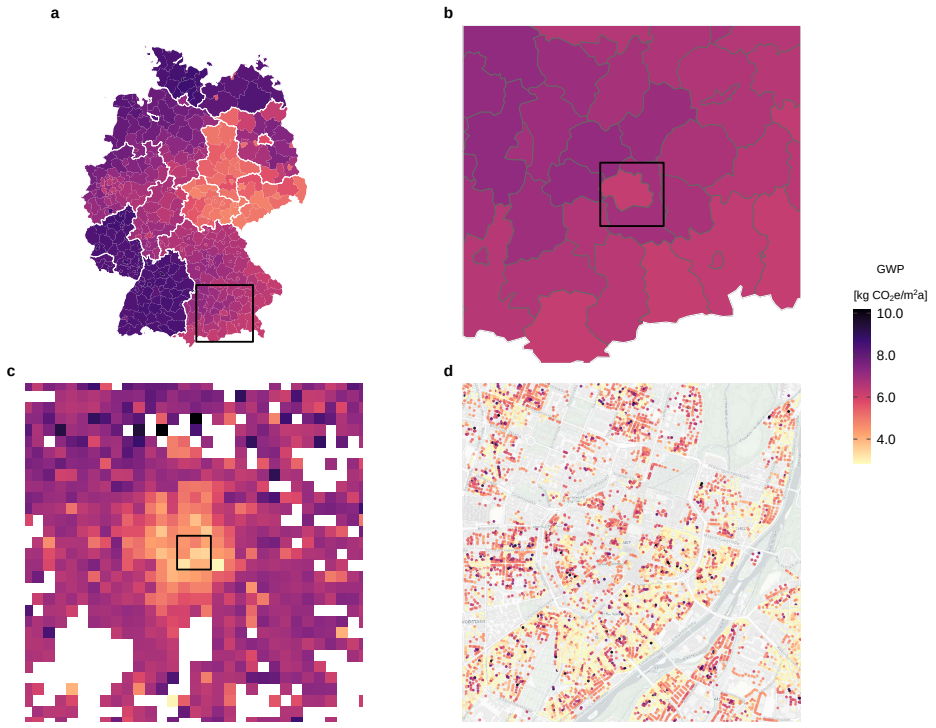


Fig. 1 Spatial distribution of building-level embodied carbon. Embodied carbon aggregated to (a) federal states, (b) districts, (c) 1-km grid cells[33] and (d) the individual building. Zoom rectangles connect successive panels. Grid cells with no residential buildings are white in (c). Panels inherit a shared color scale.

importance of accounting for individual building geometries when estimating embodied carbon intensity.

Intensity also rises with in younger building age classes (Fig. 2b). The pre-1919 cohort (BAC1) contains 4.2 kg CO_2e/(m^2·a), consistent with its lime-mortar construction and its near-absence of reinforced concrete. Intensity then climbs through the post-war age classes as reinforced concrete and heavier constructions became standard[29, 31]. The 74% of the stock built between 1949 and 1978 (BAC3 to BAC5) sits at 7.2–7.8 kg CO_2e/(m^2·a) (Fig. 2b). Taking single-family homes for example, intensity in BAC9 is approximately twice that in the BAC1 cohort at comparable net-floor-area-to-footprint-area ratios (Fig. 2c).

Because every building is estimated individually, the account further resolves to any geographic level (Fig. 1). Mean intensity spans 5.7 to 8.4 kg CO_2e/(m^2·a) across federal states, lowest in Saxony and highest in Schleswig-Holstein, 5.0 to 9.2 across the 400 counties, and 5.1 to 8.5 for the middle 80% of one-kilometer grid cells. Aggregating removes the extremes but leaves the center of the distribution almost untouched. Within a typical county the middle 80% of buildings still spans 5.2 to 9.1 kg CO_2e/(m^2·a), as wide as the entire range between county means. A county mean

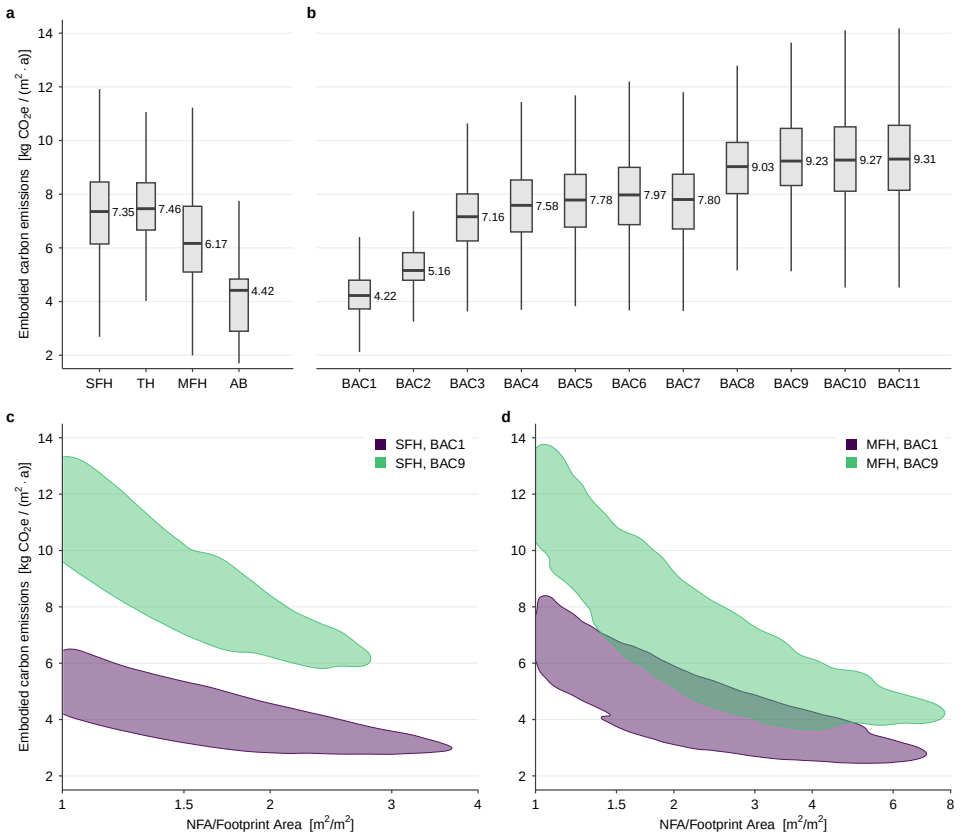


Fig. 2 Embodied carbon heterogeneity across the stock. Panels (a) and (b) show per-area embodied carbon by size class and by building age class (BAC). Identification of BACs is documented in Supplementary Table 2. Boxes in (a) and (b) give the interquartile range and median of the building-level distribution. Whiskers extend to 1.5× the interquartile range, and outliers are suppressed for legibility. Panels (c) and (d) present embodied carbon intensities of single-family houses (c) and multi-family houses (d) built before 1919 (BAC1) or in the period 2002-2009 (BAC9) against their respective net floor area (NFA) to footprint area ratio. Each shape encloses 99% the buildings in each cluster, derived from a kernel-smoothed density of all buildings. We also refer to Supplementary Figure 2 for building surface area distributions for further understanding of the stock-level heterogeneity.

therefore says little about the buildings inside it, which archetype-based assessment cannot recover.

This bears directly on the EPBD limit values now being written into German law[15]. A limit expressed per square meter of floor area meets three difficulties. It binds hardest on the smallest buildings, which carry the highest intensities. It can be met by building larger, since a bigger building spreads emissions over more floor area, so more than one functional unit is needed[35]. And it says nothing about how efficiently that space is then used, which building codes already disregard when they reward equipment and envelope upgrades[36]. Underlying all three, limit values are still derived from archetypes rather than from the budgets they are meant to serve, which

risks misdirecting decarbonization[2]. A distribution measured building by building is what such a limit should be calibrated against.

Emissions from end-of-life treatment dominate the stock's remaining embodied carbon and are contingent on whether buildings are retained

We further decomposed every building into its lowest- and highest-impact construction across the three life-cycle module groups (Fig. 3a). Floor-area-weighted across the stock, embodied carbon intensity spans 3.2 to 11.6 kg CO_2e/(m^2·a). The product stage (A1–A3) is the most variable, showing an interval between 1.2 and 8.6 kg CO_2e/(m^2·a). Its share of the total life-cycle embodied emissions climbs from 37% at the lower bound to 74% at the top. Replacement (B4) and end of life stages (C3–C4) are tightly bounded by comparison, at 0.1–0.7 and 1.9–2.2 kg CO_2e/(m^2·a), respectively. The range inherits the size ordering of Fig. 2a, widening from 2.2–7.2 kg CO_2e/(m^2·a) for apartment buildings to 3.6–12.7 for terraced houses. Almost all of that spread is carried by the product stage (Table 1). The smallest buildings are therefore not only the most carbon intense but also the most sensitive to how they were built.

The three modules separate carbon already spent from carbon still to come. The product stage is emitted in full when a building is constructed. What remains divides into two quantities that differ in whether they can be avoided at all. Replacement recurs for as long as a building stands and cannot be avoided while it is in use. However, the end of life stage is the largest share and is incurred only in case of deconstruction. For a single-family house, for example, modules B4 and C3–C4 together account for 2.2 to 3.3 kg CO_2e/(m^2·a), of which 0.1 to 0.8 is replacement and 2.1 to 2.5 is end-of-life (Table 1). Almost all of the stock's remaining embodied carbon therefore hangs on a decision that has not yet been taken.

Keeping buildings in use defers that decision indefinitely, the case for doing so is well established[37], and holds across national accounting methods[38–40]. Refurbishing to an advanced energy standard costs a fraction of the production-stage energy of demolishing and rebuilding it to the same standard and delivers more than twice the cumulative saving over three decades[41]. Rebuilding to raise energy performance buys comparatively little and costs a great deal of material[42]. Regulating operational energy alone does not remove this impact but displaces it into the product and replacement stages[1, 43]. Building with bio-based materials is the obvious response, but it is a conditional one. Timber structures carry roughly a third of the product-stage carbon of reinforced concrete, and that advantage holds even when biogenic uptake is left out of the account[44]. But storing carbon in buildings transfers it from forests to cities, and supply and land limit how far material substitution can be taken[44–46].

Our own decomposition shows what that convention does in practice. Resolved by building age (Fig. 3b and Supplementary Table 13), the product-stage minimum is negative for the oldest age classes and the three most recent. In these cohorts the lowest-impact option for several components is timber-based, whose biogenic uptake is booked in the product stage. Incineration at end of life is chosen by default in our data, which returns the stored carbon to the atmosphere, whereas recovery and reuse

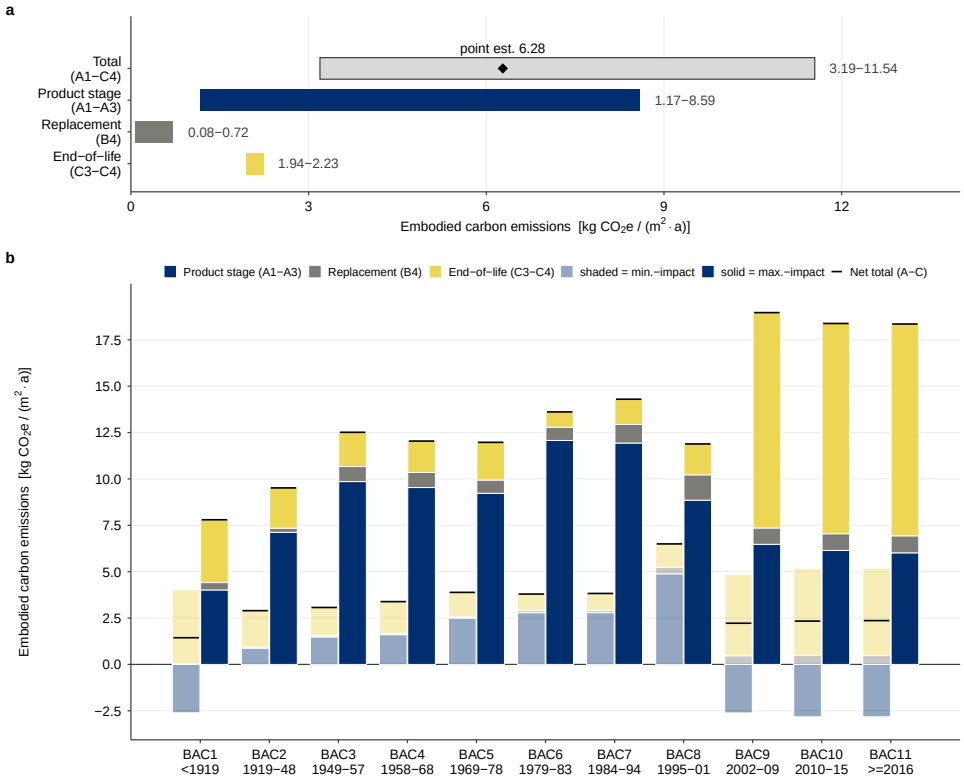


Fig. 3 Life-cycle module range of the standing stock's embodied carbon. (a) National floor-area-weighted ranges of the embodied carbon total (A1–C4) and of its three modules: product stage (A1–A3), replacement (B4) and end-of-life (C3–C4). Each spans the minimum- to maximum-impact construction. The stock aggregate (6.3) is marked with a black diamond. (b) The same decomposition resolved by building-age classes (BAC1–11), with paired bars for the minimum-impact (shaded) and maximum-impact (solid) construction of each cohort (numerical values in Supplementary Table 13). The life-cycle modules stack to the embodied carbon total, marked by the net-total tick (A–C). The product stage is negative in age classes whose minimum-impact construction is timber-based, which stores biogenic carbon at construction and releases it again at end of life. Because that storage counts as a credit, the replacement and end-of-life stages together add up to more than the net total. We refer to Supplementary Notes 1 and 2 for further details. All values in kg CO_2e/(m^2·a).

would raise the reduction potential above every other option[47]. Retention sidesteps the question, because a building that remains in use does not reach its end of life during the period for which its service life is extended. Where components do get replaced, reusing them on site postpones the disposal emissions instead of incurring them[39], and reuse can outperform recycling[48]. Retention is therefore the strongest instrument available for the embodied carbon of the standing stock. It is also not what climate policy asks of it, which is that these buildings be brought to an advanced efficiency standard.

Table 1 Life-cycle module range of the German residential stock by building size class. Minimum- and maximum-impact bounds of the embodied total and of its module groups: product stage (A1–A3), replacement (B4) and end-of-life (C3–C4) as representative range. Bounds are taken from the representative constructions of each age class, floor-area-weighted over the stock and annualized (all values in kg CO_2e/(m^2·a)). Each bound is the construction with minimum and maximum embodied carbon intensity, so within a group the minimum can exceed the maximum, as present in the C3–C4 column for apartment buildings. Size indicates size classes terraced houses (TH), single-family homes (SFH), multi-family houses (MFH), and apartment buildings (AB). n is the building count in millions.

		Total		A1–A3		B4		C3–C4	
Size	n [Mio.]	min.	max.	min.	max.	min.	max.	min.	max.
TH	1.57	3.62	12.71	1.61	9.30	0.11	0.83	1.91	2.57
SFH	14.93	3.39	12.43	1.23	9.16	0.09	0.80	2.07	2.48
MFH	2.84	2.85	10.11	1.07	7.78	0.06	0.57	1.73	1.76
AB	0.08	2.23	7.21	0.45	5.14	0.05	0.44	1.73	1.64

Retrofitting the stock to an advanced energetic standard could consume most of the building sector's carbon budget

The standing stock will not be left as it is, because buildings have to be retrofitted if Germany is to meet its climate-neutrality goals for operational emissions. National retrofit activity has barely moved since 2000, largely because renovation does not pay for itself[49, 50]. Germany's buildings strategy asks for 1.7 to 1.9% of floor area to be retrofitted each year until 2045. Buildings are to reach the Efficiency House (EH)70 standard between 2025 and 2040 and the more demanding EH55 standard from 2040[11]. EH70 limits renovated buildings to 70% of the primary energy demand compared to an equivalent reference building and EH55 to 55%, respectively. We quantify the embodied carbon consequences of retrofitting Germany's residential building stock to the enhanced EH55 standard. It is worth noting that our retrofit building constructions represent current conventional building practice. This means that insulation, for example, is mostly non-bio-based. Our retrofit constructions do not contain ecologically optimized material variants, such as low-carbon concrete, or clay. Hence, the retrofit scenarios we model represent a business-as-usual and not a best-practice scenario to achieve the optimal environmental solution.

EH55 retrofit constructions are applied to the thermal building envelope. We tested five different annual retrofitting rates from 0.5 to 2.5% of floor area, and four scenarios differing in the order buildings are treated: oldest first (Scenario 1), largest first (Scenario 2), at random (Scenario 3), and a combination of the first two (Scenario 4). The German strategy therefore describes a shallower retrofit than we model, and our scenarios show the case Germany would face if it has to raise rate and depth at once. That case is not remote, because building-stock models put the annual rate needed for 1.5 °C alignment at 2.4%[51], well above both the strategy and current German practice.

A top-down allocation of the global carbon budget leaves the German building sector 490 Mt CO_2e of embodied carbon for 2025 to 2045[14] (assuming 1.7 °C target at 83% probability). How mitigation should be divided between sectors is itself

contested[52], so the size of the budget depends on choices we inherit. Those 490 Mt have to cover every intervention in the sector over two decades, new construction as well as renovation, and non-residential as well as residential buildings.

Across the five retrofit rates Scenario 1 emits 93 to 708 Mt, Scenario 2 62 to 638 Mt, Scenario 3 73 to 685 Mt, and Scenario 4 91 to 698 Mt CO_2e. That is between 13 and 145% of the remaining budget for the whole building sector in Germany (see also Supplementary Table 15). At the rates federal strategy asks for the four converge, consuming 44 to 84% of the budget at 1.5% per year and 59 to 114% at 2%. Retrofitting also changes what the standing stock continues to emit. The emissions from replacement and end-of-life treatment are 2.0 to 3.0 kg CO_2e/(m^2·a) (Fig. 3a). Retrofitting raises that to 2.1 to 4.5 kg CO_2e/(m^2·a). Only part of this rise is caused by the retrofit itself. At 2% per year it is 99 to 280 Mt of the 287 to 559 Mt total. The rest falls on components a retrofit leaves in place, which have to be replaced and disposed of in any case.

Which buildings are treated first matters most at slow and fast retrofit rates. At 0.5% per year the highest scenario produces 51% more than the lowest and at 2.5% per year 15% more, against 5% at 1.5%. A slow rate treats too little of the stock for the scenarios to overlap, while a fast rate exhausts the never-refurbished buildings at different points (Methods). The budget consequences therefore cannot be sequenced away. But if Germany is forced to raise its retrofit ambitions, the ordering becomes an instrument worth considering. Treating the largest buildings first (Scenario 2) is the carbon-cheapest scenario at every rate, producing 26 Mt less than oldest-first (Scenario 1) at 2% per year and 70 Mt less at 2.5%, or 5 and 14% of the sector budget. This advantage arises from the same geometry that sets the intensity gradient of Fig. 2a.

Which materials a retrofit uses influences embodied emissions as much as how fast the country retrofits. At 2% per year the same scenario emits 305 Mt if the lowest-impact conventional construction is used, and 549 Mt if the highest-impact one is. Raising the retrofit rate from 1.5 to 2.5% per year moves that total by 176 to 298 Mt. Material choice is therefore a relevant lever, but only the retrofit rate is currently subject to policy. At building scale, substituting materials already on the market cuts the embodied carbon of a deep retrofit by around 20%[53], and insulation alone accounts for much of that[48]. Across Europe such a shift ranks below operational efficiency and space demand when levers are compared by average effect[9]. If which materials a retrofit consumes weighs as heavily as how often retrofits happen, then a retrofit has to be assessed on the carbon it embodies and not solely on the energy it saves. It is therefore essential that retrofitting be carried out using ecological materials and low-carbon construction methods that generate little to no additional life-cycle based carbon emissions, because retrofitting using conventional practices will likely miss climate targets. But, the recast European EPBD sets embodied carbon limit values only for new buildings and provides no counterpart for renovation[15].

What remains of the sector budget cannot be spent on retrofitting alone, because demand for housing is still climbing. Supplying steel and cement within the carbon budget would meet roughly 40% of projected demand for construction[54, 55], so new construction has to shrink its own claim before the retrofit's can be settled. Part

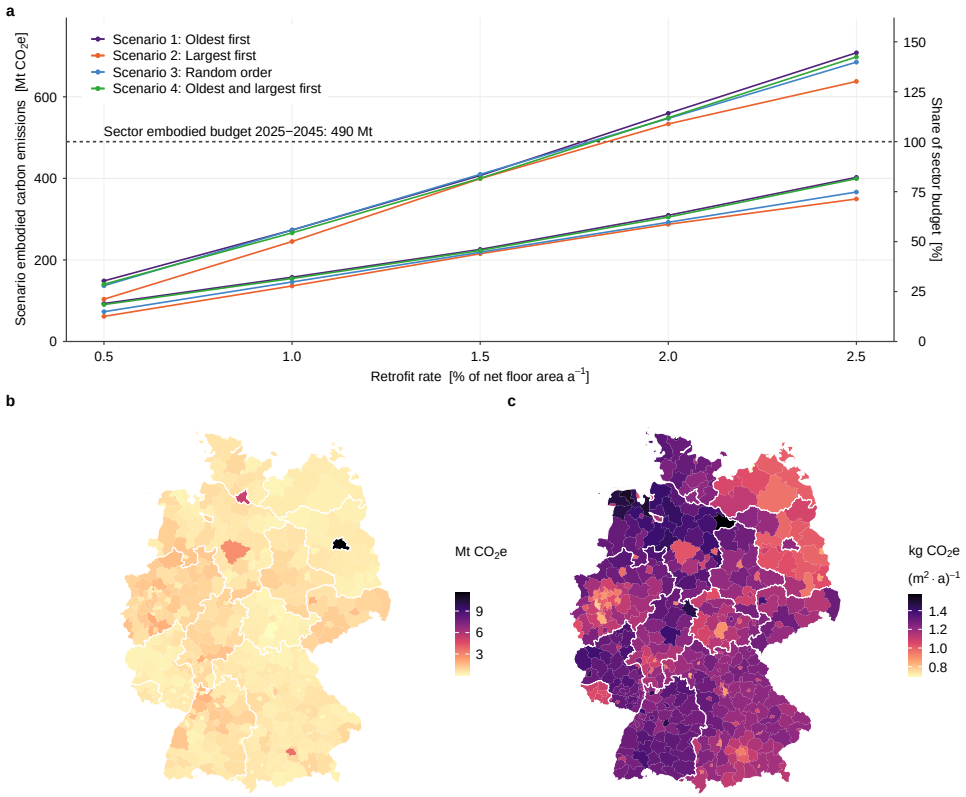


Fig. 4 Embodied carbon of retrofitting the standing stock to an advanced efficiency standard. (a) Scenario embodied carbon (Mt CO_2e, A1–C4) against the annual retrofit rate. For each of the four retrofit strategies, which differ in the order in which buildings are treated, the range spans the minimum to maximum embodied carbon resulting from the choice of lowest-impact or highest-impact materials construction. The panel therefore captures three dimensions of the retrofit pathway: retrofit rate, material choice, and retrofit strategy (order). This is everything the stock still emits under a given scenario, combining the replacement and end-of-life emissions carried forward by the components a retrofit leaves untouched with the life-cycle of the retrofit constructions themselves. Scenario 1 treats the oldest construction cohorts first, Scenario 2 retrofits multi-family houses and apartment buildings before single-family and terraced houses, Scenario 3 draws at random, and Scenario 4 combines the first two. All scenarios place buildings completed after the 2002 energy-saving ordinance last in priority. The dashed line marks the 490 Mt CO_2e embodied budget allocated to the German building sector for 2025 to 2045[14], and the right axis reads the same quantity as a share of it. Panels (b) and (c) Embodied emissions attributable to the retrofit itself, by county, for Scenario 4 at 2% per year, assuming the highest-impact construction throughout: (b) in absolute terms, and (c) normalized on the county's whole net floor area over the 50-year reference period. Panel b reads as a map of how much building each county contains, and panel c as the allocation each county would carry per unit of its own floor area. The scenario applies a single national retrofit rate with no spatial targeting, so neither map is a prioritization. The life-cycle module decomposition of the scenario total is given in Supplementary Fig. 5 and the same scenario assuming a heated attic in Supplementary Fig. 6. We provide stock coverage of all retrofit scenarios in Supplementary Table 15.

of that gap is recoverable on the supply side, through best-available technology[56],

material efficiency in lighter design, substitution and longer service lives[37, 57, 58], and circular strategies[59, 60]. The larger part lies in how much floor area is built at all[61, 62]. Yet even Europe's most ambitious sufficiency scenario assumes about 42 square meters of floor space per person[63], and aiming for decent living standards would add a tenth to today's global material stock[64]. Even with both sides pressed, a residential retrofit wave remains one claimant among several on an already short budget.

Building sector's carbon budget accounting should include embodied emissions

Embodied emission from retrofits are allocated heterogeneously across the country. Under Scenario 4 at 2% per year, assuming the highest-impact construction variant, retrofitting adds 273 Mt CO_2e nationally. Berlin alone accounts for 11.5 Mt of that, Hamburg for 5.2 Mt, Munich for 3.7 Mt, the Hannover region for 2.9 Mt and Cologne for 2.0 Mt (Fig. 4b). The ten largest counties carry 13% of the national total emissions. Measured against each county's own floor area, retrofit embodied carbon emissions range from 0.69 to 1.57 kg CO_2e/(m^2·a) (Fig. 4c). Counties where single-family houses dominate carry the most, based on the gradient shown in Fig. 2a. The county is the scale at which construction is governed[7], and for cities the scale at which net-zero plans are written[65].

Embodied emissions are upstream, Scope 3 emissions, and Germany allocates them to the industry sector instead of buildings[11]. So, the sector that prescribes the retrofit is not the sector that carries the corresponding emission budget, which is common across Europe[65]. The emissions from producing the materials therefore sit outside those inventories by design. What is needed is a consumption-based account of construction that includes emissions produced elsewhere[7] and city inventories extended to scope 3 emissions[65]. A city that retrofits its housing meets the consequence directly, because the emissions its own net-zero plan causes fall outside the inventory that plan is measured against. A compensation strategy therefore cannot cover what it has never quantified. Fig. 4c is the missing figure for all counties in Germany.

Policy recommendation

Part of the carbon in Germany's homes has already been emitted, but the carbon they will still cost has largely not, and how much of it is spent depends on three decisions that current policy neither asks nor accounts for: whether a building is kept, what it is retrofitted with, and where the resulting emissions are counted.

Whether a building is kept decides the largest part of the stock's remaining embodied carbon emissions, because these emissions surface only when it is deconstructed. Climate policy asks whether a building meets an efficiency standard, not whether it is kept. Retention should therefore be treated as a climate measure.

What it is retrofitted with decides whether the retrofit fits within climate limits. With conventional constructions, retrofitting the stock to an advanced standard would consume most of the building sector's embodied carbon budget for the next two

decades and could exceed it. Using low-carbon materials, in contrast, would spend far less. A retrofit therefore must be assessed on the carbon it embodies, not only on the energy it saves.

Embodied carbon limits exist for new buildings but not for renovation, so a benchmark for retrofits is the missing instrument. Where the emissions are counted decides whether this cost is seen by those who cause it. The emissions a retrofit causes are not booked to the building sector, so the sector that prescribes the retrofit does not carry its emissions, and the cities whose net-zero plans require it cannot see them in the inventories those plans are measured against. Bringing the embodied carbon of construction into those accounts, at the county level where construction is governed, would make the cost visible where the decision is taken.

Methods

Study design and system boundary

This is a descriptive, bottom-up accounting. Our work establishes a spatially explicit embodied carbon estimate, a life-cycle module decomposition of the standing stock, and a prospective retrofit scenario built on both. The life-cycle boundary follows DIN EN 15978[66]. Our indicator is the embodied global warming potential (GWP) over life-cycle modules A1–A3 (product stage), which cover raw-material supply, transport and manufacturing, module B4, which covers component replacement, and modules C3–C4, which cover end-of-life waste processing and disposal. Modules A4–A5, B1, B2, B3, B5 and C1–C2 lie outside our scope. The operational modules B6–B7 are excluded by definition, because they represent operational emissions and not embodied. We express GWP intensity per unit of net floor area (NFA) and annualized it over a reference study period of $T = 50$ years, consistent with DIN EN 15978 and with most German building studies (Supplementary Table 18). The functional unit is therefore one kilogram of CO_2-equivalent per square meter of net floor area per year.

Building-level input data

Building geometry came from ETHOS.BUILDA[27, 28], a geo-referenced dataset covering the entire German residential stock, which supplies each building's footprint area, height, net floor area, construction year, roof shape and size class. The composition of the input stock is summarized in Supplementary Table 6.

Component-level carbon intensities came from our construction database, which documents the life-cycle embodied global warming potential over modules A1–A3, B4 and C3–C4 of more than 1,000 German building constructions. Each construction is resolved by component type, building-age class (BAC) and construction family, and it is measured per unit of component area, for example per square meter of exterior wall. This life-cycle module scope dictates the scope of our assessment.

The complete database is provided as Supplementary Data 1–3, and its use in our estimation is described in Supplementary Note 2 and below. Because life-cycle-inventory intensities are approximately log-normally distributed[67, 68], we summarized each pool of eligible constructions by its geometric mean. The

distributional analysis and the full construction-intensity ranges are given in Supplementary Note 2.

We used the TABULA residential typology[30, 31] to reconcile the two datasets, since both adopt TABULA's building-age and size-class definitions, and to supply typical geometric ratios such as window-to-wall ratios where building-specific values were unavailable.

Computing building-level embodied carbon

We assigned each building i to a class defined jointly by its construction period and its size. The eleven building-age classes $b \in \{\mathrm{BAC1}, \ldots, \mathrm{BAC11}\}$ follow the TABULA period definitions[31]. They run from the pre-1919 stock (BAC1), through the inter-war, post-war and late-twentieth-century cohorts, to the most recent construction from 2016 onward (BAC11), as listed in Supplementary Table 2. We derived each building's age class from its construction year as given by the ETHOS.BUILDA dataset and read its size class $s \in \{\mathrm{SFH}, \mathrm{TH}, \mathrm{MFH}, \mathrm{AB}\}$, namely single-family house, terraced house, multi-family house and apartment building, directly from the same record. This joint classification is what harmonizes the three datasets.

ETHOS.BUILDA[27, 28] and our construction database both adopt the TABULA age-band and size-class definitions, so a building's class selects both the typical geometric ratios that complete its component areas and the construction pool that supplies its carbon intensities. The age class additionally carries the era-level correlation in construction practice on which our uncertainty analysis rests, because the constructions of a given period tend to share materials and detailing.

We organize constructions into three families representing construction scenarios: *OldBuilding* (age-typical construction as built), *RefurbishedBuilding* (a prospective energetic upgrade) and *NewConstruction* (replacement to passive-house standard). We fixed the family to *OldBuilding* for every building, so that our embodied carbon account describes the standing stock as originally built.

Three properties of the data require this. First, ETHOS.BUILDA assigns its refurbishment attribute probabilistically to reproduce federal-state shares[28, 69] and so cannot locate refurbishment nor refurbishment timing at the individual building level. Second, in the *RefurbishedBuilding* family the production modules (A1–A3) of retained layers are set to zero and they therefore do not share a module boundary with *OldBuilding* constructions. Third, *RefurbishedBuilding* constructions are defined only as a minimum–maximum range and allow no pooled estimate. According to the ETHOS.BUILDA dataset, some of the stock has been refurbished. So we note that, the standing German residential stock embodies more carbon than our estimation captures, which is an increment neither dataset can resolve currently (Supplementary Note 2).

We evaluated ten structural components $c \in \mathcal{C} = \{\mathrm{Roof1}, \mathrm{Roof2}, \mathrm{Wall1}, \mathrm{Wall2}, \mathrm{Floor1}, \mathrm{Baseplate}, \mathrm{Foundation}, \mathrm{Slab}, \mathrm{InteriorWall}, \mathrm{Window}\}$. Roof1 is a roof element exposed to external air, which can be pitched or flat. Roof2 is the top-floor ceiling bordering unheated spaces such as a cold attic. Wall1 indicates an external wall facing outdoor air. Wall2 is a wall in contact with soil. Floor1 is the ceiling above an unheated cellar. Baseplate is the ground-bearing slab covering the footprint, and Foundation

the strip or pad footings beneath it. Slabs are all vertically separating structures not classified as Roof2, Floor1, or Baseplate.

Construction intensities $\mathrm{gwp}_{c,k}$ are indexed by c and a building-class key $k = (b, \sigma)$ that reduces to the age class b once the family σ is fixed to *OldBuilding*. Because the specific construction installed in any individual building is unknown, we pooled eligible constructions for each component and key into a set $\mathcal{A}_{c,k}$ and used its geometric-mean intensity $\overline{\mathrm{gwp}}_{c,k}$. In all further descriptions uppercase GWP denotes *building-level aggregates* and lowercase gwp denotes *component-level intensities* ($\mathrm{kg\,CO_2e/m^2}$).

We estimated building-specific component areas $A_{c,i}$ from ETHOS.BUILDA geometry, supplemented by size-class-specific ratios from TABULA[31] and our construction database[29] where direct measurement was not possible. The reference net floor area $A_{\mathrm{NFA},i}$ was taken directly from ETHOS.BUILDA. The building total embodied carbon and its annualized, area-normalized intensity therefore are given as

$$\mathrm{GWP}_i = \sum_{c \in \mathcal{C}} A_{c,i}\, \overline{\mathrm{gwp}}_{c,k_i}, \qquad k_i = (b_i,\ \mathit{OldBuilding}), \tag{1}$$

$$\mathrm{GWP}_{\mathrm{m^2a},i} = \frac{\mathrm{GWP}_i}{A_{\mathrm{NFA},i}\, T}, \tag{2}$$

where $\overline{\mathrm{gwp}}_{c,k_i}$ is the geometric-mean component-level embodied carbon intensity for key k_i and $T = 50$ years.

The building footprint sets the ground-contact and roof areas. The wall height, obtained by subtracting the roof height from the building height, together with an assumed storey height sets the number of storeys and hence the intermediate-slab area. The external-wall area follows from the net floor area through a ratio that varies by size class, construction period and building size bin. The window and interior-wall areas follow in turn from the external-wall area through size-class-specific ratios. The area estimation rests on a set of uniform assumptions. Terraced houses are treated as detached, the cellar is 2 m high, non-flat roofs are given a 35° pitch, and the storey height is 2.5 m. These assumptions and the full set of area equations are stated and justified in Supplementary Note 2.

The building-level results aggregate to any spatial unit $\mathcal{G}$, by summing embodied carbon and net floor area over the buildings it contains,

$$\mathrm{GWP}_{\mathrm{m^2a},\mathcal{G}} = \frac{\sum_{i \in \mathcal{G}} \mathrm{GWP}_i}{T \sum_{i \in \mathcal{G}} A_{\mathrm{NFA},i}}. \tag{3}$$

This floor-area-weighted aggregation is mass-conserving, so the national total is preserved at every scale.

Module decomposition

We resolve each construction's gwp into the three life-cycle module groups A1–A3, B4 and C3–C4, and report this split for two representative constructions of each component and age class, namely the minimum- and maximum-impact construction. A detailed derivation of minimum- and maximum-impact is given in Supplementary

Note 2. A module split of the pooled geometric-mean intensity would require the module vector of every construction in the pool, and our data does not provide it. The life-cycle modules are in any case not additive under the geometric mean, so we do not decompose the point estimate GWP_i directly. We keep GWP_i as the estimate of the A–C total and carry the module information as an additive minimum–maximum range alongside it (Supplementary Note 2).

For each component c and class key k, we take the two representative constructions with the lowest and the highest reported environmental impact and read their module intensities $\mathrm{gwp}_{c,k}^{m,\min}$ and $\mathrm{gwp}_{c,k}^{m,\max}$ for each module group $m \in \{\mathrm{A1–A3}, \mathrm{B4}, \mathrm{C3–C4}\}$. Applying these intensities to the building's own component areas bounds building i by module group,

$$\mathrm{GWP}_i^{m,\min} = \sum_{c \in \mathcal{C}} A_{c,i}\, \mathrm{gwp}_{c,k_i}^{m,\min}, \qquad \mathrm{GWP}_i^{m,\max} = \sum_{c \in \mathcal{C}} A_{c,i}\, \mathrm{gwp}_{c,k_i}^{m,\max}. \tag{4}$$

Because each bound is a single construction rather than a per-module extremum, its three module groups sum exactly to the corresponding bound of the building total. This additivity is preserved at every level of spatial aggregation.

The three module groups map onto the timing of the emissions and define the partition we use throughout. Group A1–A3 is the product stage which is released at construction. Group B4 is the recurring replacement of components over the service life. Group C3–C4 is the contingent end-of-life stage, incurred only when a building is demolished.

Quantifying construction-choice uncertainty

Two uncertainties act on the point estimate, and we quantified them separately. The first is the estimator itself. We used the geometric mean because life-cycle inventory data are skewed[67, 68], and by the arithmetic-mean–geometric-mean inequality (see Supplementary Note 3.4) it lies at or below the intensity expected if the installed construction were drawn uniformly from its pool. The point estimate is therefore a systematic lower bound relative to that uniform prior. The second is construction choice, which we quantified with an empirical bootstrap Monte Carlo over 672 populated archetypes of federal state, age class and size class, evaluated on a representative subsample of 6.5 million buildings. For each archetype we report the estimator bias, a geometric standard deviation as a multiplicative dispersion measure, and an empirical 90% interval. That interval is a prior-conditional dispersion under the uniform-choice assumption and not a confidence interval for the true stock value. Deterministic minimum and maximum scenarios, which substitute each pool's extreme intensity for every component at once, complement the independent sampling, so the two together bracket any monotone cross-component correlation. These stress bounds are distinct from the module range of equation (4), which is built from representative constructions. The full procedure is outlined in Supplementary Note 3.

We further cross-checked our estimation model against a documented bottom-up assessment of a Munich district[29], reproducing the reported range with a small upward offset attributable to a difference in sample size (Supplementary Note 5,

Supplementary Table 17). Our intensities come from a single national construction database, and the choice of underlying life-cycle inventory is itself a material source of variation between assessments[70].

Prospective retrofit scenario

Our database documents a second construction family, *RefurbishedBuilding*, which describes each age-typical construction after an energetic renovation to the EH55 standard. Efficiency House 55 (EH55) limits the renovated building to 55% of the primary energy demand of an equivalent reference building. In a retrofit scenario we applied this construction family to the standing stock.

The renovated family carries a different module boundary from the *OldBuilding* family. For a renovated component it accounts for four things: the end-of-life (C3–C4) of the layers stripped out to carry out the retrofit, the product stage (A1–A3) of the layers newly installed, the replacement (B4) of the whole post-renovation construction over the following 50 years, and the end-of-life (C3–C4) of that construction at the end of them. Insulating a masonry external wall from outside therefore counts the production of the insulation and of the new render or cladding, the disposal of any surface layer stripped to fit them, the replacement of both over the next 50 years, and the disposal of the whole wall at the end of that period. It does not include the product stage (A1-A3) of the masonry, which was released when the building was built. A retrofit intensity therefore replaces the as-built intensity of the component it applies to, and is not added to it.

We retrofitted the thermal envelope $\mathcal{E} = \{\text{Wall1}, \text{Window}, \text{Roof2}, \text{Floor1}\}$, namely the external wall, the windows, the ceiling below an unheated attic and the floor above an unheated cellar. This treats the attic as unheated, which keeps the insulated plane at the top-floor ceiling rather than at the roof. A variant that assumes insulation of the roof instead is reported in Supplementary Note 5.7. Windows carry no renovation construction, since a window is assumed to be replaced, so they take the end-of-life of the old window together with the full life-cycle emissions of a new one from the *NewConstruction* family. A retrofitted building then produces

$$\begin{aligned} \mathrm{GWP}_i^{\mathrm{retrofit}} = &\sum_{c \in \mathcal{E}} A_{c,i} \left(\mathrm{gwp}_{c,k_i^{\mathrm{ren}}}^{\mathrm{A1–A3}} + \mathrm{gwp}_{c,k_i^{\mathrm{ren}}}^{\mathrm{B4}} + \mathrm{gwp}_{c,k_i^{\mathrm{ren}}}^{\mathrm{C3–C4}} \right) \\ &+ \sum_{c \notin \mathcal{E}} A_{c,i} \left(\mathrm{gwp}_{c,k_i}^{\mathrm{B4}} + \mathrm{gwp}_{c,k_i}^{\mathrm{C3–C4}} \right), \end{aligned} \tag{5}$$

where the first sum runs over the components the retrofit touches and the second over those left in place. $A_{c,i}$ is the area of component c in building i, estimated exactly as in the baseline, so a retrofit changes no geometry. k_i^{ren} is the class key of that building considering the renovated family and k_i the same key considering the *OldBuilding* family. Each renovated component contributes all three of its module groups, because the renovation installs new layers whose production, replacement and disposal all follow from the decision. Each retained component contributes only replacement and end-of-life, since these are the emissions its continued service still

entails (Supplementary Note 1). The product stage of the *OldBuilding* construction, $\mathrm{gwp}_{c,k_i}^{\mathrm{A1–A3}}$, appears in neither sum. These emissions have already been spent and a retrofit neither incurs it again nor avoids it, so adding it would charge the retrofit for emissions released decades earlier. We call this the *scenario embodied emissions* of building i.

Retrofit intensities were selected exactly as the module range is, by ranking each component-and-age pool once on the A1–C4 total and taking its minimum- and maximum-impact construction. Of the 220 component-and-age combinations, 109 carry a negative product stage, because a lot of the renovation constructions make use of wood-fibre insulation, which stores biogenic carbon at production and releases it at end of life[71]. All 220 A1–C4 totals, however, are positive.

We applied annual retrofit rates of 0.5 to 2.5% of national NFA in steps of 0.5, and accumulated the corresponding emissions over 2025 to 2045 inclusive. This window is exactly aligned with[14]. The interval spans the retrofit rate of roughly 1% per year observed in Germany over the past two decades and the 1.7 to 1.9% per year the federal buildings strategy asks for[11]. No individual retrofit is dated, and the standard 50-year reference study period of each renovation starts when its building gets retrofitted.

Eligibility for retrofittings followed the ETHOS.BUILDA refurbishment attribute, which labels buildings *existing*, *usual* or *advanced*. Buildings in the *existing* state represent unrefurbished observations (see Supplementary Table 6 for the distribution between unrefurbished and refurbished buildings) and were treated first. Those in the *usual* state once the first group was exhausted, and those in the *advanced* state never. *Usual* and *Advanced* refurbishments represent conventional and advanced energetic upgrades, respectively [30, 31]. Because the refurbishment attribute is assigned probabilistically in the ETHOS.BUILDA dataset and identifies no individual building, results are stock-level quantities throughout.

Within the eligible stock we evaluated four scenarios, which differ only in the order buildings are treated: by age from oldest to newest (Scenario 1), by size with multi-family houses and apartment buildings before single-family and terraced houses (Scenario 2), at random (Scenario 3), and a combination of the first two (Scenario 4). Any one of the scenarios places buildings completed after the German 2002 energy-saving ordinance (hence BAC9 to BAC11) last in priority (Supplementary Table 14).

The scenario total embodied emissions were compared against the embodied carbon budget of 490 $\mathrm{Mt\,CO_2e}$ that Woytowicz et al.[14] allocate to the German building sector for 2025 to 2045. Based on [72], the authors obtained this budget by downscaling the remaining global budget for a 1.7 °C target to Germany on an equal-per-capita basis, then to the building sector on its share of national emissions, and then to the embodied share of those. Since their budget covers the same three module groups over the same window and prices each intervention over its whole life-cycle, we can compare our estimation against their.

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- supplementarydata03.xlsx
- SM.pdf
- supplementarydata04.xlsx
- supplementarydata01.xlsx
- supplementarydata02.xlsx