

Whole-life carbon emissions and material demand in the Swedish building stock: an archetype-based stock dynamics assessment

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Abstract

The construction sector is a major contributor to global greenhouse gas (GHG) emissions and material use, with embodied emissions from materials increasingly dominating total life-cycle impacts, particularly in countries where operational emissions are declining. This study presents a novel, integrated modelling framework for assessing material demand and life cycle GHG emissions from building construction at the national level, applied to Sweden through 2045. The model combines detailed archetype-based life-cycle assessment (LCA) with dynamic stock-driven projections and scenarios for reduced construction volumes, material efficiency, substitution with bio-based materials, and decarbonization of energy system and material production via electrification and bioenergy with carbon capture and storage. It captures variations in material use across building typologies, frame types, and components, while allowing for scenario-based assessment of structural material flows and emissions reductions over time. Results for all life-phases show that concrete remains the most material- and emission-intensive component, particularly in multi-family and non-residential buildings. However, scenario comparisons (that focus on A-phase improvements) indicate that emissions can be reduced by 90% in year 2045, in line with the national sectoral roadmap, but do not yet lead to carbon neutrality. Further efforts in decarbonizing the operational side and energy system are required to achieve full neutrality. The analysis identifies key leverage points (how and when) for further emissions reduction across the sector and provides a replicable approach to national-level, scenario-based building sector decarbonization.

1. Background

The production of construction materials accounts for 23% of global greenhouse gas (GHG) emissions (Pauliuk et al., 2021), with the construction sector consuming 40% of materials in bulk globally (González-Torres et al., 2022; Ingrao et al., 2019). Among these materials, concrete production alone contributes an estimated 8% of annual global GHG emissions, with an annual production volume of around 4 billion tons (Lehne and Preston, 2018), while the steel industry is responsible for 7–9% of global GHG emissions (International Energy Agency, 2020). Construction is one of the largest users of these materials with around 29 % of steel and 46 % of cement consumption being used for buildings (Cembureau, 2025; Rostek et al., 2022),

At the end of the material life cycle, the European construction sector generates 820 Mt of construction and demolition waste annually—equivalent to 46% of all waste produced—of which concrete, ceramics, and masonry make up as much as 85% (Gálvez-Martos et al., 2018). Landfilling remains the dominant disposal method for end-of-life construction materials globally (Kookos et al., 2019). These analyses are consistent with the global material flows and carbon impacts outlined in the IPCC Sixth Assessment Report (Cabeza et al., 2022), which emphasizes the significant role of material use in building-related emissions.

Still, until recently, most policy initiatives and progress within the building sector have primarily targeted GHG emissions generated from the operations of built assets such as heating, cooling, and lighting (IEA, 2023; United Nations Environment Programme, 2023).

Operational energy and emissions have usually been considered greater than embodied energy and emissions, with the former representing 70–80% of total energy and emissions expenditure and the latter 10–30% (Akbarnezhad and Xiao, 2017; Ingrao et al., 2019; Röck et al., 2023). However, a global study comprising 650 life-cycle assessment (LCA) case studies, has found a clear trend of increased embodied emissions due to improvements in energy efficiency, representing 45–50% of life cycle emissions in high-efficiency buildings, or even up to 90% in some extreme cases (Röck et al., 2020). This shift underscores the necessity of addressing GHG emissions across all life cycle stages (Cabeza et al., 2022).

In Sweden, embodied emissions already constitute the majority of emissions from the built environment (Boverket, 2025a), unlike at the EU level, where operational emissions remain dominant (European Commission, 2023). Consequently, efforts to reduce emissions in Swedish building sector have adopted a whole life cycle approach, why the case of Sweden particularly relevant to study. Measures targeting both heating systems and material production are particularly important for achieving net zero emissions in the long term.

To align the building sector with the climate targets in the Paris Agreement, an 8% annual reduction from 2020 would be required globally (UN Environment Program, 2019). However, global emissions from the sector have remained constant over the past 5 years (IEA; 2023). Still, it is estimated that circular economy strategies could reduce annual global GHG emissions from key industrial materials (e.g. cement, steel, plastic and aluminum) by 40% by 2050 (EMF, 2019). The largest potential emission reductions result from more intensive use of buildings and their lifetime extension (Hertwich et al., 2019), and improved material recycling and reuse (Alaux et al., 2024; Hertwich et al., 2019; Lotz et al., 2024), combined with decarbonization of material production (Alaux et al., 2024; Karlsson et al., 2020). Complementarily, material efficiency strategies could reduce cumulative global greenhouse gas emissions by 28–72 GtCO_{2e}, corresponding to 1/3–2/3 of total GHG emissions for residential buildings by 2060 (Pauliuk et al., 2021).

Achieving these reductions requires a comprehensive understanding of its carbon footprint, inclusive of both new construction and the existing building stock (Nordic Sustainable Construction, 2024)(Cabeza et al., 2022). Despite the growing recognition of life-cycle emissions, most scenario-based studies addressing decarbonization at national or global scales have focussed either on operational emissions (see e.g. the reviews in Mata et al, 2020 and Porolfsdottir et al, 2030 and articles there in) or embodied emissions (Lotz et al., 2024; Zhong et al., 2021). A few studies adopt a combined perspective; for example, (Mastrucci and Ruijven, 2023) analyses scenarios of low energy and material demands for global residential buildings, while (Alaux et al., 2024) investigate GHG reduction strategies from a life cycle perspective. In Sweden, there has also been a government-initiated industry-driven fossil-free roadmap development (Fossil Free Sweden, n.d.). This has set targets and overall commitments for value chain actors, but lack an analysis of measures (Fossil Free Sweden, 2024). While these studies provide valuable context and system-level insights, a more detailed and granular analysis is needed for a better understanding of opportunities and challenges linked to specific development paths towards a resource efficient and circular building sector.

This study contributes to that gap by integrating the most updated knowledge from different focus areas (material industry, buildings energy efficiency, climate scenario modelling) and aggregation levels (construction material, building element, building typology, national building stock). National-scale LCA of building stock, when coupled with future scenario analysis, provides a detailed accounting of current and future embodied and operational

emissions. Such an approach allows for informed projections of how construction practices, material use, and the building stock may evolve over time under different policy or technological trajectories.

These insights are crucial for designing decarbonization strategies that are effective, cost-efficient, and aligned with long-term climate goals. By integrating LCA and scenario modelling, stakeholders can identify key intervention points, optimize resource use, and prioritize measures that balance emission reductions with economic feasibility. This forward-looking approach supports adaptable strategies capable of responding to emerging trends and uncertainties in the built environment.

2. Aim

We aim to develop and apply a modelling framework that integrates detailed building typologies with dynamic stock modelling and life cycle assessment. The model is applied to the Swedish building sector through 2045 under different development pathways. The objective is to quantify associated energy use and GHG emissions and evaluate the potential for emission reductions through improved material use strategies. The following questions are considered:

- What is the current distribution of building materials across building typologies and components in Sweden?
- What could be the future demand for key structural building materials - concrete, steel, and timber - in new construction?
- How can strategies such as material efficiency improvements, climate-smart production, and substitution with lower-impact materials reduce the whole life-cycle (WLC) emissions in the building stock?

3. Method

A modelling framework integrating archetype-based LCA, dynamic stock modelling, and scenario analysis was developed to assess WLC GHG emissions from the Swedish building stock. The framework extends the ECCABS modelling framework (Mata et al., 2024, 2020, 2013a) to include all life cycle phases according to EN 15978 (CEN, 2012), encompassing material production (A1-A3), construction (A4-A5), use phase (phases B1-B7), and end of life processes (C1-C4). Phase D (benefits beyond system boundaries: re-use, recovery, recycling) is excluded.

Several assumptions were aligned with previous studies to facilitate comparability and validation, including the scenario pathways from (Karlsson et al., 2020), simplified modelling of phase C from (Erlandsson and Pettersson, 2015), and assumptions on building stock dynamics. The methodology combines detailed archetype descriptions of the building stock with future socioeconomic and technological scenarios affecting both operational and embodied emissions.

Operational energy use is modelled for the entire building stock, while embodied emissions from construction are calculated only for new construction, as emissions associated with the existing stock have already occurred. Annual WLC emissions therefore consist of emissions from new construction, renovation activities, operational energy use, and end-of-life treatment of demolished buildings.

The Swedish building stock is represented through archetype buildings, established through segmentation, quantification, characterization and validation (Mata et al., 2014). The methodology for building-stock description has been extensively applied in previous studies to derive archetypes for operational energy analysis, so it will only be briefly summarized in section 1.1. It is nevertheless here for the first time implemented to derive archetypes relevant for a WLC analysis including phases A1-A5 and C1-4 (below-described in 3.3.4), which constitutes one of the methodological novelties of the paper.

The stock description distinguishes between the existing building stock and buildings constructed in the baseline year. This distinction is necessary because operational emissions are associated with the existing stock, whereas embodied emissions from construction are only calculated for newly constructed buildings.

3.1. Building stock description

3.1.1. Existing stock

The existing building stock is represented through archetypes established based on the segmentation categories building typology, construction period, climate zone, heating system, ventilation system, and building size. Residential buildings constructed up to year 2005 (included) are represented through 1384 sample buildings from the so-called BETSI project (*Energi i bebyggelsen - tekniska egenskaper och beräkningar*, n.d.; *Teknisk status i den svenska bebyggelsen*, n.d.), whereas non-residential buildings constructed up to 2010 are represented by 336 archetypes, as described in earlier work (Mata et al., 2018, 2015, 2015, 2014, 2013b). The remaining construction periods are represented through archetypes for buildings constructed during 2006-2021 and 2010-2021 for residential and non-residential buildings, respectively.

In the characterization for B6, each archetype is described by the thermal properties of the building envelope, ventilation systems, heating systems, domestic hot water demand, indoor temperature assumptions, and building geometry (Mata et al., 2013a). Floor areas for single family buildings are obtained from (Energimyndigheten, 2023a), and for multi-family buildings from (Boverket, 2023), and for non-residential buildings from (Energimyndigheten, 2023b). For buildings constructed after 2006, building geometry is based on the floor areas determined in the segmentation, where the total envelope area is derived the same envelope-to-heated-floor-area ratio as in the original samples. Unknown surfaces of envelope (such as facades, cellars, roofs and windows) and building geometry are estimated using the 3CL-DPE Method, based on heated floor area, number of storeys, assumed building form, and attachment conditions to neighbouring.

Properties of the construction materials are assumed to follow building standards for the corresponding construction periods. Hot water demand is assumed 25-30 kWh/m², depending on the building type (NIKANDER and AHLQVIST, 2020). Characteristics of the energy systems are based on (Boverket, 2020; Mata et al., 2020, 2018). For residential buildings constructed up to year 2005, the characterization from earlier work is maintained, with adjustments in U-values to reflect historical improvements in energy efficiency. These adjustments are based on national statistics from (Energimyndigheten, 2025a, 2025b) attributed proportionally to the share of energy used for space heating relative to heating demand (86% and 78% for SFB and MFB, respectively). Similar adjustments are applied for non-residential buildings built before 2010 using average values from (Energimyndigheten,

2023c). The resulting annual energy efficiency improvement was 1.1%, 0.9% and 1.0% for SFB, MFB and non-residential buildings, respectively.

In the quantification step, the frequency of each archetype in the stock is represented through weighting coefficients following Equation 1 and previous ECCABS applications (Mata et al., 2024), using updated statistics (Energimyndigheten 2023a-c) and with a coefficient for the relationship between buildings and dwellings. For existing residential buildings, statistics on dwellings and buildings are combined (Energimyndigheten, 2023a, 2023c). As statistics for MFB are primarily reported in number of apartments, an average number of apartments per building is first calculated using data from (Boverket, 2023). The weighting coefficients are subsequently derived using distributions for heating systems, building size, ventilation systems, climate zones, and building typologies.

3.1.2. Construction in the baseline year

To model embodied emissions from new construction, additional archetype descriptions were developed for buildings constructed in the baseline year 2022. In contrast to the existing stock archetypes primarily developed for operational energy analysis, the segmentation for phase A was expanded to include parameters relevant for material demand and embodied emissions. The number of archetypes was defined based on parameters relevant to the study's objectives and constrained by data availability.

For phase A, one additional variable was introduced: structural *frame type*. This variable was combined with the segmentation criteria already established for Phase B in previous studies. The resulting archetype set comprises 840 distinct combinations, derived from 16 building typologies, building sizes, construction year, 3 types of heating system, 4 types of ventilation, 4 climate zones, 4 types of frame-type, PV (binary variable). The non-residential building typologies are based on a differentiation used by (Energimyndigheten, 2023d).

In the characterization relevant for phase A1-A5, each archetype is assigned materials intensities (in kg¹/m²) for concrete, reinforcement steel, construction steel, insulation, gypsum and plaster, plastics and chemicals, aluminium, glass, and timber. The data is assigned by matching the archetypes to an openly accessible dataset of 68 projects with reference values for climate impact developed by (Boverket, 2023; Malmqvist, 2023).

Although the dataset does not directly provide material demands, it includes all construction products used in each building. These products could be input in the BM calculation tool (*Byggsektorns Miljöberäkningsverktyg* (Sidvall, 2023)) to calculate material demand (kg/m²) and climate impact assigned resource groups for all archetypes. Resources not presented in mass units were converted into kilograms using resource-specific conversion factors integrated in the BM-tool (Boverket, 2023).

The resulting material calculations covered life cycle stages A1-3 (product stage), A4 (transportation) and A5 (waste, packaging, and waste management), following standard EN15978 (CEN, 2012). The system boundary corresponds to the Swedish regulations for climate declaration of buildings valid in 2022, and encompasses building parts 2-6 of the

¹ In general, the energy and emissions related to the operation of buildings, i.e. B6 are often related to the heated floor area (HFA) of a building, while the embodied energy and emissions related to building construction and maintenance can be related to either the HFA, the useful floor area or the gross floor area (GFA). In the Swedish regulation and practice, it is often related to the GFA. As such, the results of material use, energy and emissions in the results sections will be presented either in relation to HFA or GFA. On average, the ratio HFA/GFA is 0.9 for the sampled buildings (Malmqvist et al, 2023).

SBEF building parts table (Boverkett, 2024), i.e. foundation, load bearing structural frame, roof, facades, non-load bearing elements. The calculations were validated by comparing the total climate impact resulting from the BM-tool for phases A1-A5 with the corresponding values in Boverkets dataset (Malmqvist, 2023). Detailed comparison results are provided in Supplementary Material (SM1_Climate impact).

Reports detailing material demand per resource group were generated for each building (See Supplementary Material, SM2_Material demand). These were subsequently harmonized into broader material categories aligned with the groupings in Karlsson et al, 2020, thereby facilitating comparison with validation data and scenario assumptions while maintaining sufficient detail to address the research questions.

Since there was no complete data coverage across all archetypes, the following assumptions were made: if material demand data existed for one or more buildings matching a specific archetype, an average of those buildings was used; if there was no match of archetype, averaged data for the same type of building and frame type (i.e. excluding differences related to ventilation, region and PV option) was used; for non-residential buildings without data for a matching typology and frame, averages were drawn from non-residential buildings with the same frame type. For archetypes without any applicable data (covering 12% of the total floor area), material demands were based on available data from similar archetypes and adjusted according to expected differences in material composition (Table 1).

Table 1. Material demand (kg/m² HFA) used as default from archetypes with unknown material composition. This affects 12% of the floor area.

Concrete	Reinforced Steel	Construction Steel	Insulation	Gypsum and plaster	Plastics and Chemicals	Aluminium	Glass	Timber
600	10	16	12	16	0.3	0.3	1.5	30

In the quantification step, the frequency of each archetype i in the national stock in year 2022 is represented by a weighting factor W , calculated as a share of the total number of buildings:

$$W = NB_{Totb,j} \times P_{HS_k} \times P_{DS_l} \times P_{VS_m} \times P_{PV_o} \times P_{FT_p} \quad \text{EQUATION 1}$$

Where $NB_{Totb,j}$ is the total number of buildings per building type b and climate zone (based on data per region which is allocated to a climate zone) j , obtained from (Energimyndigheten, 2023d, 2023e). ; P_{HS_k} is the percentage of buildings per heating system k , obtained from (Energimyndigheten, 2023a, 2023b, 2023e); P_{DS_l} is the percentage of buildings per dwelling size l , obtained from (Energimyndigheten, 2023a, 2023b, 2023d); P_{VS_m} is the percentage of buildings per ventilation system m , obtained from (Boverkett, 2023) (Table 2); P_{PV_o} is the percentage of buildings with PV option o ; and P_{FT_p} is the percentage of buildings per frame type p .

P_{PV_o} is estimated per climate zone using installation statistics disaggregated into three power categories: <20 kW, 20-1000kW and >1000 kW (Energimyndigheten, 2025c). Installations in the lowest category were assumed to be associated with single-family homes, while the

middle category was evenly distributed between multifamily and non-residential buildings. PV installations influences both embodied emissions in construction phases (A1-A5) and operational energy during the use phase (B6).

Table 2. The share of ventilation system options P_{VS} .

	FTX VAV	FTX CAV	FX	Other
SFB	0%	9%	55%	36%
MFB	0 %	74%	0%	26%
Non-residential	13%	40%	0%	47%

Table 3. percentage of total (new and existing) buildings with PV per climate zone and building typology, in baseline year 2022 (Energimyndigheten, 2025c). SFB, Single family building; MFD, multifamily building; NR, non-residential building.

Climate Zone	SFB	MFB	NR
1	2%	10%	4%
2	4%	11%	4%
3	5%	14%	8%
4	4%	14%	5%

$P_{FT,p}$ is calculated for the different building types based on a combination of construction data and expert opinions (Table 4). Nearly all existing SFB have wooden frames. For MFB, the distribution was calculated as the average historical data for the period 2016-2022. Due to data limitations for non-residential buildings, frame type distributions were estimated combining sparse empirical data with expert opinions.

Table 4. Distribution of frame types among building typologies, including sources. SFB, Single family building; MFD, multifamily building; NR, non-residential building.

Frame type	SFB (Malmqvist, 2023)	MFB (SCB, 2025a)	NR: Special dwellings (Malmqvist, 2023)	NR: Educational (Malmqvist, 2023)	All other NR typologies (Malmqvist, 2023)
Concrete	-	80%	64%	53%	52%
Wood	99%	17%	18%	27%	20%
Steel	-	2%	18%	20%	28%
Other	1%	1%	-	-	-

3.2. Stock dynamics

Future construction is modelled using a stock-driven dynamic approach applied in other studies (Bergsdal et al., 2007; Hu et al., 2010; Pauliuk et al., 2013) that combines projections of future demand for new buildings with assumptions regarding renovation and demolition rates.

The number of new residential buildings ($NB_{Tot,b,j}$) in each future construction period t , is determined by the population growth, latent building need, and lifestyle parameters (i.e. persons per dwelling and average floor area per dwelling):

$$NB_{Tot,b,j} = SBC_j * \frac{\left(\frac{PG_t}{PPD_{b,t}} + LBN\right) * PRD_b}{DPB_b} \quad \text{EQUATION 2}$$

Where SBC_j is the share of dwellings located in climate zone j in the baseline year (Energimyndigheten, 2023d, 2023e, p. 3); PG is the estimated population growth during construction period t (SCB, 2025b); $PPD_{b,t}$ is the average number of persons per dwelling for building type b and period t (SCB, 2024); LBN is the latent building need, defined as the current deficit in dwellings needed to house the population adequately (Boverket, 2025b); PRD_b is the residential dwelling percentage by building type b , i.e. the distribution between single-family and multifamily dwellings (Energimyndigheten, 2023b, 2023a); DPB_b is the average number of dwellings per building for building type b , obtained for multifamily buildings from (Boverket, 2023) and for single family buildings by combining data from SCB (SCB, 2025c) and Energimyndigheten (Energimyndigheten, 2023a). the resulting variables NB_{Tot} , combined with updated projections of PV installations, are then used to calculate new weighting coefficients, following equation 1, for all the archetypes of the baseline year.

For non-residential buildings, the new heated floor area of all building types (Energimyndigheten, 2023e) was assumed proportional to the total heated floor area of new residential construction. These proportions were calculated using recent national statistics on building permits (SCB, 2025d).

Renovation and demolition rates govern stock turnover. A renovation rate of 1% of the total building stock was assumed in the baseline scenario for both residential and non-residential buildings. Renovations are assumed to primarily consist of energy-efficiency measures affecting operational energy demand while also generating embodied emissions associated with phase B5. Demolitions are represented through a fixed annual demolition rate applied to buildings constructed before 2005, following previous Swedish studies (Erlandsson, 2020; Naturvårdsverket and Boverket, 2019). Due to the relatively low demolition rate in Sweden, demolished buildings were assumed to have limited influence on future stock composition.

3.3. WLC emissions

The annual WLC emissions of the building stock ($Em_{WLC})_{Tot}$ are:

$$(Em_{WLC})_{Tot} = Em_{A1-3} + Em_{A4-5} + Em_{B1} + Em_{B4-5} + Em_{B6} + Em_{C1-4} \quad \text{EQUATION 3}$$

Where the emissions of each phase are calculated as described in the corresponding subsections below.

3.3.1. Production (A1-3)

The total annual emissions in A1-A3 for the new construction in the building stock are calculated as the sum of the emissions per material m and archetype i , for all archetypes:

$$(Em_{A1-3})_{Tot} = \sum_i \sum_m (M_{i,m} * ((EIF_{pr,m} + Qf_m * \sum_s (q_{m,s} * EmI_s)) * (1 - CC_m) + Qf_m * q_{m,el} * EIF_{el})) \quad \text{EQUATION 4}$$

where Em (kg CO_{2e}) is the emissions resulting from the material production; $M_{i,m}$ (kg) is the material demand of material m calculated in the model as below described; $EIF_{pr,m}$ (kg CO_{2e}/kg) is the process emissions intensity factor to produce material m ; Qfm (kWh/kg) is the energy intensity factor for production of material m ; qm,s (%) is the share of direct energy sources s for the production of material m ; EmI_s (kg CO_{2e}/kWh) is the emissions intensity factor of direct energy source s ; CCm (%) is the share of direct and process emissions captured via carbon capture technologies in the production of material m ; qm,el (%) is the share of energy use from electricity in the production of material m ; $EIFel$ (kg CO_{2e}/kWh) is the emissions intensity factor of electricity; all given in (Karlsson et al., 2020).

The material demand $M_{i,m}$ (kg) for each building archetype i and material m is:

$$M_{i,m} = HFA_i * MD_i \quad \text{EQUATION 5}$$

Where HFA_i is the heated floor area (m²_{HFA}) of each archetype i and MD_i is the material demand (kg/m²_{HFA}) for each archetype i , both given as an input.

3.3.2. Construction (A4-5)

The annual emissions for A4 Em_{A4} (kg CO_{2e}), are calculated as the sum of all material categories m as:

$$(Em_{A4})_{Tot} = \sum_i \sum_m (M_{i,m} * EF_{i,m}) \quad \text{EQUATION 6}$$

Where M_m (kg) is the total annual mass of material m being transported per archetype i , and EF_m is the averaged emission factor (kg CO_{2e}/kg) for transportation of each material. Data for some archetypes are extracted from BM-tool. For those archetypes not present in the detailed data, standard emission factors, EF_m (kg CO_{2e}/kg), from (Malmqvist, 2023) for each material category are used as seen in the table below.

Table 5. Emission factor (kg CO_{2e}/kg) for transportation of each material from (Malmqvist, 2023).

Material	Emission factor
Concrete	0.0039 kg CO _{2e} /kg
Prefabricated concrete	0.045 kg CO _{2e} /kg
Reinforcement Steel	0.0795 kg CO _{2e} /kg
Construction Steel	0.0795 kg CO _{2e} /kg
Insulation	0.0345 kg CO _{2e} /kg
Gypsum and Plaster	0.24 kg CO _{2e} /kg
Plastic and Chemicals	0.0345 kg CO _{2e} /kg
Aluminium	0.0495 kg CO _{2e} /kg
Glass	0.042 kg CO _{2e} /kg
Timber	0.0345 kg CO _{2e} /kg

The emissions for the construction equipment (A5), are calculated using energy intensity EI (kWh/m²_{GFA}) and emission factor EF (kg CO_{2e}/kWh) from (Malmqvist, 2023) (Table 8). This is assumed to be equal for all building types and calculated as:

$$(Em_{A5})_{Tot} = HFA_{Tot} * \sum_s (EI * EF) \quad \text{EQUATION 7}$$

Table 6. Set standard quantities of various energy products for calculating module A5 Energy in the project and use climate data for energy products (Malmqvist, 2023). GFA, gross floor area.

Energy source	Standard amount	Emission factor
Electricity	68 kWh/m ² GFA	0.037 kg CO ₂ e/kWh
District heating	69 kWh/m ² GFA	0.088 kg CO ₂ e/kWh
Diesel	30 kWh/m ² GFA	0.075 kg CO ₂ e/MJ
LPG	46 kWh/m ² GFA	0.084 kg CO ₂ e/MJ
Fuel oil	29 kWh/m ² GFA	0.082 kg CO ₂ e/MJ

3.3.3. Use phase (B1, B5 and B6)

Carbonation during use (B1)

The total annual CO₂ uptake from carbonation is calculated with a standard annual sequestration rate of $-4 * 10^{-5}$ kg CO₂/ kg based (IVL, 2024) as:

$$(Em_{B1})_{Tot} = -4 * 10^{-5} * Mc_{Tot}$$

Where Mc_{Tot} (kg) is the total mass of concrete within the building stock.

Renovations (B5)

The emissions from renovation measures are calculated as:

$$(Em_{B5})_{Tot} = \sum_b RR * REF * A_{tot,b} * CE_b$$

Where RR (%) is the renovation rate, REF (%) is the renovation emissions factor, $A_{tot,b}$ (m²_{GFA}) is the total floor area of building type b , and CE_b (kg CO₂/m²_{GFA}) are the construction-phase embodied emissions for building type b .

Based on data from pilot studies, the renovation emissions factor is assumed to correspond on average to 16% of the embodied emissions associated with equivalent new construction (Andersson and et al, 2025). In the underlying study, embodied emissions vary from 40 kgCO₂e/m²_{GFA} to close to 160 kg CO₂e/m²_{GFA} (96 kgCO₂e/m²_{GFA} on average). Renovation measures are assumed to primarily consist of energy-efficiency improvements that reduce operational energy demand and exclude emissions from installations and internal surface finishes.

Operational Energy Use (B6)

Operational emissions from the building stock were calculated using the modelling framework ECCABS described in multiple studies.

$$(Em_{B6})_{Tot} = \sum_i Em_{B6,i} * W_i$$

Where $Em_{B6,i}$ is the operational energy use emissions per building archetype i and W_i is the archetype weighting coefficient.

3.3.4. End-of life (C1-4)

To estimate emissions from life cycle phase C, a fixed annual demolition rate of 0,01% of the total floor area is applied to buildings constructed before 2005 (Erlandsson, 2020; Naturvårdsverket and Boverket, 2019), which are assumed to exhibit material distributions and intensities equivalent to phase A archetypes. Due to limited alignment between older

building descriptions and new-construction archetypes, average material intensities per building type are used.

The annual demolished floor area Ad_{tot} (m^2_{GFA}) is calculated as:

$$Ad_{tot} = 0.0001 * \sum_b NB_{pre2005,b} * A_b \quad \text{Equation 8}$$

Where NB_b is the number of buildings of type b constructed before 2005, and A_b (m^2_{GFA}) is the average floor area for building type b .

The total material waste mass W_m (kg) for each material m generated annually is (Erlandsson, 2020):

$$W_m = \sum_b Ad_{TOT} * PA_b * M_{f,b} \quad \text{EQUATION 9}$$

Where PA_b (%) is percentage of the total GFA coming from building type b , and $M_{f,b}$ (kg/m^2_{GFA}) is the average material intensity in building type b .

Deconstruction and demolition (C1)

Emissions from preparatory deconstruction and demolition activities Em_{C1} are calculated as the sum of emissions from general demolition activities (Em_{PD}) and additional work related to frame types ($Em_{FT,s}$) and building height (Em_{HS}):

$$Em_{C1} = Em_{PD} + Em_{FT} + Em_{HS}$$

Subsequently, Em_{C1} is determined from the emission intensity factor associated with energy source EIF ($kg\ CO_2e/kWh$), and the energy demand per energy source $Q_{C1,s}$ (Erlandsson and Pettersson, 2015):

$$Em_{PD} = \sum_s EIF_s * Ad_{tot} * EI_s \quad \text{EQUATION 10}$$

Where Ad_{tot} is the total demolished area and EI_s is the energy intensity per energy source (kWh/m^2) related to preparatory deconstruction work. $Q_{C1,s}$

Additional emissions are associated with specific building characteristics. For frame-specific deconstruction work for different frame types (Concrete, Wood, Steel, Other) m , these are:

$$W_{m,3} = 0.0001 * \sum_b NB_b * A_b * M_{b,3} \quad \text{EQUATION 11}$$

$$Em_{FT} = \sum_m \sum_s W_3 * EI_{m,s} * EIF_s \quad \text{EQUATION 12}$$

Where W_3 (kg) is the mass of structural frame material (building part 3) for material group m , NB_b is the number of buildings of type b , A_b (m^2_{GFA}) is the average GFA per building type b , and $M_{b,3}$ (kg) is the average frame material demand for the for building type b , $EI_{m,s}$ is the energy intensity per energy source (kWh/m^2), and EIF_s is the emission intensity factor associated with energy source s ($kg\ CO_2e/kWh$).

For structures exceeding six meters high ($Em_{HS,s}$), additional emissions are:

$$Em_{HS} = \sum_{m,s} \left(\sum_j \frac{S_j^{-2}}{S_j} * W_{j,3} \right) * EI_{m,s} * EIF_s \quad \text{EQUATION 13}$$

Where S_j is number of storeys for each archetype building j , $W_{j,3}$ (kg) is the mass of demolished structural frame material, $EI_{m,s}$ (kWh/kg) is the energy intensity per energy

source and material, and EIF_s is the emission intensity factor associated with energy source s (kg CO₂e/kWh).

Transport (C2)

Emissions from transport of demolition waste to processing facilities, Em_{C2} , are calculated as:

$$Em_{C2} = \sum_s W_{tot} * EI_t * D * EF_s \quad \text{EQUATION 14}$$

Where W_{tot} (kg) is the total annual mass of waste from all material groups, EI_t (kWh/kg km) is the energy intensity of freight transport, and D (km) is the assumed transport distance (set at 50 km), and EF_s (kg CO₂e/kWh) is the emission intensity factor of energy source s .

Waste processing and disposal (C3-C4)

Emissions (kg CO₂e) from waste processing and disposal are calculated as:

$$Em_{C3-4} = \sum_m W_m * EFd_m \quad \text{EQUATION 15}$$

Where W_m (kg) is the total annual mass of waste from material group m , and EFd_m (kg CO₂e/kg) is the corresponding disposal emissions factor, obtained from the Finnish climate database (CO2data.fi)(Erlandsson et al., 2024).

3.4. Future scenarios

Five scenarios detailing the future development of the building and construction supply chain have been developed and applied in the analysis (*Table 7*). One scenario is a business and usual (BAU) scenario, then four additional scenarios represent alternative decarbonization pathways for construction material supply chains. The scenarios differ primarily in the technological transition in material production industries and the implementation of material-efficiency measures, while the following assumptions remain unchanged across scenarios:

- Population growth, latent housing demand, persons per dwelling, and floor areas per dwelling.
- Non-residential construction demand is proportional to residential construction development.
- Energy system development follows (Morfeldt et al., 2023), and the resulting emissions factors for electricity and district heating are harmonized across life cycle phases A and B.
- Future photovoltaic (PV) shares are estimated using a linear regression model based on installation statistics for the period 2016–2022, differentiated by climate zone. The resulting PV shares in 2045 are summarized in *Table 8*.
- SFB remain predominantly timber-framed throughout the modelling period.
- Demolition rates and end-of-life assumptions.

Table 7. Summary of the investigated scenarios and their main assumptions.

Scenario	Industrial transition	Material efficiency	Renovation rate	Frame shift
BAU	Reference energy system	No	1%	None
P1	Biofuels + CCS	No	2%	Limited
P2	Electrification	No	2%	Limited
P3	Biofuels + CCS	Yes	2%	Yes

P4	Electrification	Yes	2%	Yes
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Table 8. Percentage of total (new and existing) buildings with PV per climate zone and building typology in 2045. SFB, Single family building; MFD, multifamily building; NR, non-residential building.

Climate Zone	SFB	MFB	NR
1	9%	31%	16%
2	19%	51%	15%
3	25%	52%	31%
4	17%	45%	20%

3.4.1. BAU scenario

The BAU scenario assumes continued development of the Swedish and European energy systems according to current policy and technology trends, without additional mitigation measures beyond ongoing developments in electricity production, district heating, and industrial energy efficiency.

The current distribution of frame types remains unchanged throughout the modelling period. Single-family buildings are assumed to remain predominantly timber-framed, while the shares of concrete, steel, timber, and hybrid structures in multi-family and non-residential buildings remain constant.

A renovation rate of 1% of the total building stock is assumed for both residential and non-residential buildings until 2045. Renovation measures are assumed to primarily consist of energy-efficiency improvements affecting operational energy demand while generating embodied emissions associated with phase B5.

3.4.2. Decarbonization pathways

The scenario pathways materials used in new construction (A1-A3) are based on Karlsson et al. (2020).

Pathway 1: Biofuels and carbon capture and storage (CCS), assumes the substitution of fossil fuels with biofuels across construction supply chains, combined with the implementation of CCS technologies. For cement, this involves post-combustion carbon capture using amine scrubbing. For steel, it includes top gas recycling combined with CCS. Partial biofuel use is assumed across production processes.

Pathway 2: Electrification, assumes large scale electrification of industrial processes, replacing fossil-based energy, particularly from low-carbon sources. In cement production, electrification of kiln operations is assumed. Steel production is decarbonized through hydrogen-based direct reduction and electric arc furnaces. Electrification is also assumed for other construction-related energy uses.

Pathway 3: Biofuels, CCS, and Material Efficiency, combines the technologies of Pathway 1 with additional strategies for reducing material demand. Measures include optimized concrete recipes, reduced binder intensity in concrete, increased use of secondary steel,

and material substitution (e.g., wood for structural elements). The pathway reduces emissions through both energy system transformation and demand-side efficiency.

Pathway 4: Electrification and Material Efficiency, combines electrification strategies from Pathway 2 with material efficiency measures. The scenario assumes increasing rates of electrification across all sectors, combined with efforts to reduce the volume of materials used, improve design efficiency, and promote substitution with low-carbon materials.

These pathways are implemented using the diffusion of mitigation options across pathways reported in (Karlsson et al., 2020). Across all pathways, progressive implementation of abatement measures is assumed through 2045, aligned with existing EU strategies and Swedish industry roadmaps.

3.4.3. Implementation across life cycle phases

For phase A, the scenario assumptions affect both material demand and material-production emission factors. In the material-efficiency pathways, emissions decrease due to reduced use of carbon-intensive materials and increased substitution toward timber and hybrid structures. For MFB and non-residential buildings, the share of wood or wood/concrete hybrid frames increases gradually in line with the assumptions in Karlsson et al (2020), corresponding to a 10% shift by 2045.

Transport emissions (A4) decrease indirectly in the material-efficiency scenarios due to lower material demand, despite constant emissions factors for material transport (as per Table 5). As the construction process (A5) is a minor share of the life cycle emissions, no scenario analysis is performed for this phase.

For phase B, future operational emissions are influenced by continued energy-system decarbonization, renovation measures, and increased PV installations. In the decarbonization pathways, the renovation rate is doubled compared to the BAU scenario, in line with the EU Renovation Wave strategy (European Commission, n.d.).

For phase C, demolition rates and end-of-life assumptions remain unchanged across all scenarios.

3.5. Validation

Validation, performed at five levels, compares the model results with previous Swedish studies, national statistics, and published LCA analyses.

3.5.1. Stock quantification

The quantification of the building stock was validated by comparing the resulting numbers of buildings, dwellings, and floor areas with available national statistics (Appendix A). For residential buildings, statistics on the number of multi-family buildings are limited (Energimyndigheten, 2023a) and validation therefore focuses on the number of dwellings and floor area (Energimyndigheten, 2023d; SCB, 2025c). For residential buildings, the model estimates 12% more dwellings and 8% more heated floor area than reported in national statistics. For non-residential buildings, the model estimates 6% fewer buildings and 3% more heated floor area. As statistics on non-residential premises exhibit significant variability, these differences are considered acceptable.

Validation of new construction in the baseline year 2022 shows larger discrepancies. The modelled added floor area for single-family and multi-family buildings differs by 340% and 26%, respectively, compared with available validation data. Overall, the total added residential floor area is 56% lower than reported statistics. For non-residential buildings, the total number of newly added buildings is 84% lower than validation data. These discrepancies are likely related to limitations in the underlying datasets, as no comprehensive building surveys were conducted between 2019 and 2022 and some statistics were estimated from previous observations (Energimyndigheten, 2025c).

3.5.2. Material demand and phase A emissions

To validate material demand and associated emissions, baseline results for 2022 were compared with previous literature and national statistical sources (Table A1). The resulting emissions from new building construction, including phases A1–A5, amount to 1.78 Mt CO₂e in 2022, while the corresponding material demand amounts to 5.6 Mt. These values are 20% lower than those reported by (Karlsson et al., 2020) and national statistics (Naturvårdsverket and Boverket, 2019) for reference year 2015. One explanation is that the previous studies include renovations and refurbishments covering additional building parts, such as technical installations, surface layers, fixed interiors, and groundwork. (Boverket, 2025a) reports that renovations and refurbishments correspond to approximately 60% of building construction emissions, a result corroborated by (Liu, 2025) for residential buildings.

The lower material demand may also be partly explained by differences in construction activity. Residential construction volumes were higher in 2022 than in the 2015 reference year used by Karlsson et al. (2020), both in terms of initiated and completed dwellings. Approximately 48,000 dwellings were initiated and 35,000 completed in 2015, compared with 56,000 initiated and 54,000 completed in 2022 (SCB and Byggföretagen, 2025)(Energimyndigheten, 2025a, 2025b). Construction activity declined sharply after 2022, however, with housing starts falling in connection with the economic contraction following the onset of the Ukrainian conflict (SCB and Byggföretagen, 2025).

Methodological differences also contribute to the observed discrepancies. Our study employs a process-based bottom-up LCA approach, whereas the validation studies partly on hybrid methods combining environmentally extended input-output (EEIO) and process-LCA. Previous studies have shown that EEIO analyses generally yield higher emissions than process-based LCAs due to systematic aggregation biases due to differences in system boundaries and aggregation effects (Säynäjoki et al., 2017). For example, (Karlsson et al., 2020) assumed imports of concrete elements at 2.5-3 Mt, yielding 0.4-0.5 MtCO₂e, while toll statistics indicate a maximum of 0.55 Mt, corresponding to <0.09 Mt CO₂e (SCB, 2025e). This implies that both emissions and concrete demand in the validation source are likely overestimated.

When compared with other process-based LCA studies, the results show closer agreement. Erlandsson (2020) estimated emissions from new building construction at approximately 4 Mt CO₂e in 2015 and around 2 Mt CO₂e in 2022, which is consistent with the results obtained in this study. In contrast, the EEIO-based assessment by Boverket reports emissions of 3.6 Mt CO₂e for new building construction in 2022 (Boverket, 2025a).

The distribution of emissions across life-cycle stages is also broadly consistent with previous studies (Phase A1–A3 REPRESENTS APPROXIMATELY 82% OF TOTAL A1–A5 EMISSIONS, TRANSPORT (A4) APPROXIMATELY 5%, AND CONSTRUCTION ACTIVITIES (A5) APPROXIMATELY 13%.

Table 9). PHASE A1–A3 REPRESENTS APPROXIMATELY 82% OF TOTAL A1–A5 EMISSIONS, TRANSPORT (A4) APPROXIMATELY 5%, AND CONSTRUCTION ACTIVITIES (A5) APPROXIMATELY 13%.

Table 9. Results for the baseline 2022 in this study compared with previous literature and national statistical sources for the baseline year 2015.

Emissions estimate	Building Materials (A1-A3)				Transport (A4)		Construction process (A5)	
Units	% of Phase A1-A3	% of Phase A1-A5	Mt CO ₂	Mt material	% of Phase A1-A5	Mt CO ₂	% of Phase A1-A5	Mt CO ₂
This study – baseline 2022	n.a.	81.5 [80 ¹ ; 85 ²]	1.46 [6.3 ¹ ; 6.5 ²]		5.2 [9 ¹ ; 5 ²]	0.09 [0.7 ¹ ; 0.4 ²]	13.3 [11 ¹ ; 12 ²]	0.23 [0.9 ¹ ; 0.9 ²]
Concrete	42 [44 ¹ ; 40 ²]		0.61 [2.8 ¹ ; 2.5 ²]	4.42 [17.0]				
Reinforcement Steel	4 [10 ¹ ; 10 ²]		0.06 [0.6 ¹ ; 0.6 ²]	0.08 [0.77]				
Construction Steel	9 [11 ¹ ; 11 ²]		0.14 [0.7 ¹ ; 0.7 ²]	0.06 [0.33]				
Insulation	18 [8 ¹ ; 10 ²]		0.27 [0.5 ¹ ; 0.6 ²]	0.10 [0.18]				
Gypsum and Plaster	5 [6 ¹ ; 6 ²]		0.08 [0.4 ¹ ; 0.4 ²]	0.20 [1.33]				
Plastic and Chemicals	13 [4 ¹ ; 4 ²]		0.19 [0.3 ¹ ; 0.3 ²]	0.04 [0.12]				
Other (Glass, aluminum, timber)	8 [17 ¹ ; 19 ²]		0.12 [1.1 ¹ ; 1.2 ²]	0.72 [1.82]				

¹ (Karlsson et al., 2020); ² (Naturvårdsverket and Boverket, 2019)

3.5.3. Archetype characterization

To validate the archetype characterization, the calculated embodied emissions per m² GFA were compared with median values reported by (Boverket, 2025c; Naturvårdsverket and Boverket, 2019) (Figure 1). Despite the lower total material demand estimated in this study, the resulting average emissions per m² GFA are generally comparable with the reference values. Part of the difference can be explained by system boundaries. The data reported by (Naturvårdsverket and Boverket, 2019) include technical installations and surface layers, which are not included in the present study and therefore result in higher emissions for several building categories. The results are generally consistent for residential buildings. Larger deviations occur for some non-residential building categories, likely due to the limited number of buildings represented in the underlying datasets. This is particularly the case for educational buildings in the Boverket database. In addition, the climate declaration data are based on registered declarations with limited quality assurance (Boverket, 2025c).

Some inconsistencies are observed for MFB compared with the reference data from (Malmqvist, 2023). from which the individual archetypes per frame type is based upon. These differences are likely related to the scaling procedures used when transferring material inventories between buildings of different sizes and technical characteristics. Where data exist for one archetype but not for a similar building size, scaling factors are applied to estimate material quantities per m² GFA. This may lead to under- or overestimation of specific materials.

Additional uncertainty is associated with the "Other buildings" category, which represents approximately 10% of the non-residential building stock and includes industrial, logistics, warehouse, traffic, and communication buildings. For this category, material demands are

average values from other archetypes. While reference values are available for logistics and warehouse buildings (Borgström et al., 2025), similar studies are largely lacking for industrial buildings, which may have substantially higher concrete demands (Rodrigues et al., 2018).

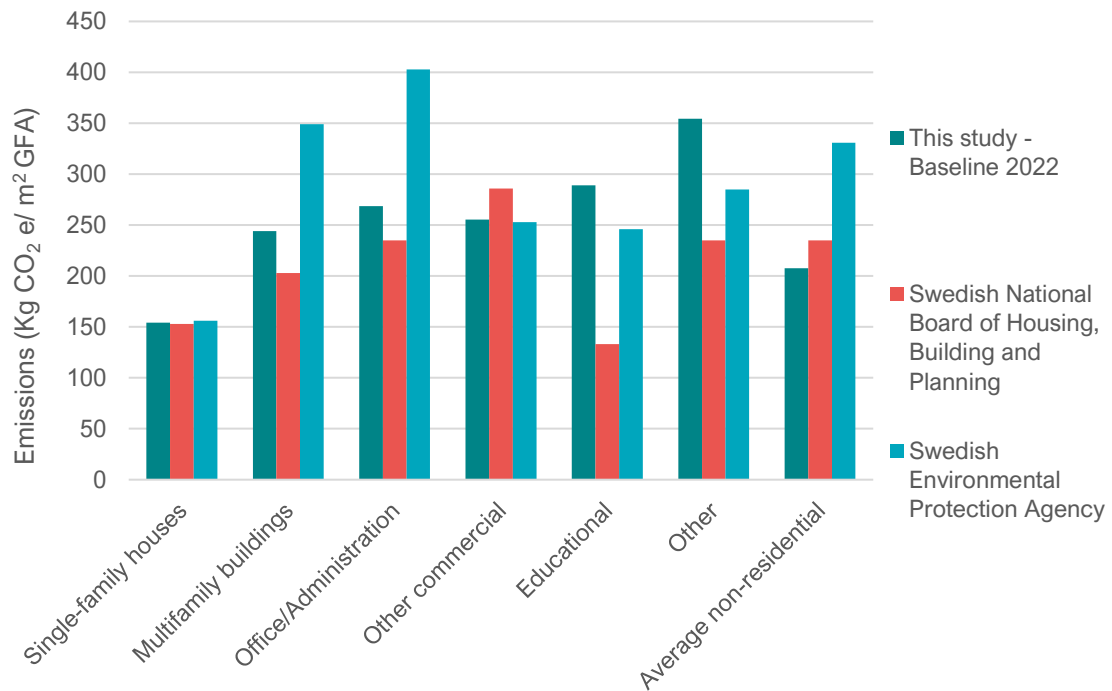


Figure 1. Emissions in year 2022 by building typology (Kg Co₂e/m² GFA), for the baseline in this study and existing literature (Boverket, 2025c; Naturvårdsverket and Boverket, 2019).

3.5.4. Operational energy performance

To validate the operational energy calculations (phase B6), the calculated final energy demand in 2022 was compared with national statistics from Eurostat (Eurostat, 2025) (Figure 2). The calculations slightly underestimate the energy demand from both the residential and non-residential building sector by 5-13%. Given the uncertainties associated with building-stock statistics, archetype characterization, and reported national energy data, this level of agreement is considered satisfactory.

Additional consistency checks were performed by comparing average U-values and primary energy performance across building types and construction periods. The results show expected improvements in thermal performance for newer buildings and demonstrate compliance with the corresponding national regulatory requirements. These comparisons provide further confidence that the archetypes adequately represent the evolution of the Swedish building stock. (Figures S1–S2 in the Supplementary Material, SM3_Energy show average U-values and primary energy performance by building type and construction period.)

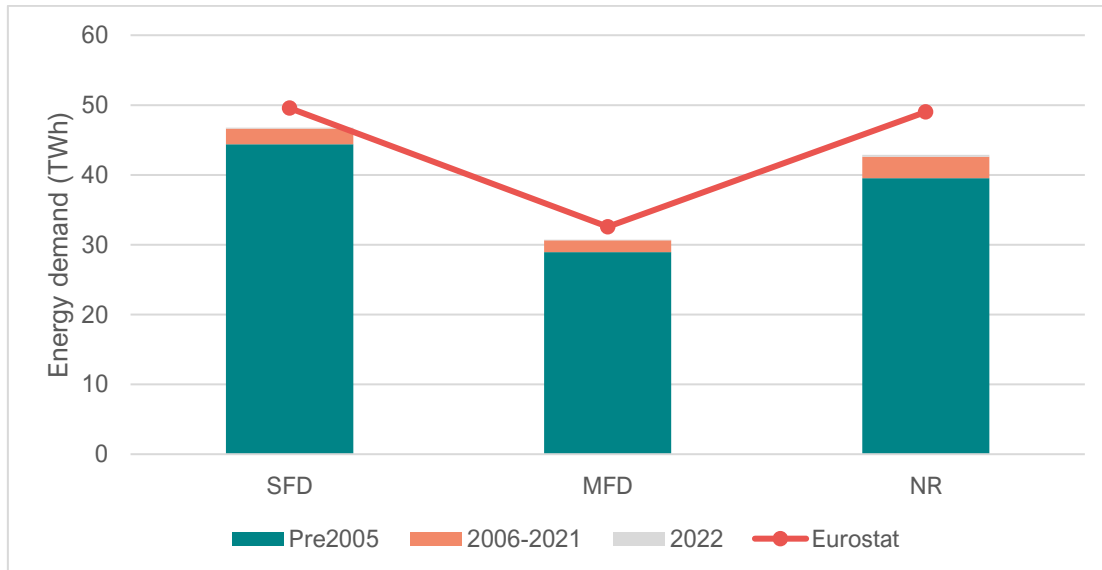


Figure 2. Total final energy demand (phase B6) in 2022 by building typology compared with Eurostat statistics.

3.5.5. End of life emissions

The end-of-life module was validated by comparing the calculated emissions for life-cycle phases C1–C4 with estimates reported by Erlandsson and Pettersson (2015). For demolition and deconstruction activities (C1), the model estimates emissions of approximately 6 kg CO₂e/m² GFA compared with 7 kg CO₂e/m² GFA in the reference study. Similar differences are observed for transport activities (C2). For waste processing and disposal (C3–C4), the model estimates approximately 39 kg CO₂e/m² GFA compared with 30 kg CO₂e/m² GFA reported by Erlandsson and Pettersson.

Overall, the results indicate good agreement for demolition and transport activities, while somewhat higher emissions are estimated for waste processing and disposal. The differences are primarily attributable to updated emission factors and assumptions regarding waste treatment pathways.

4. Results

4.1. Current allocation of building materials

4.1.1. Material intensity by building type

The calculated average material demand per m² constructed heated floor area for buildings constructed in 2022 is presented in Figure 3. As concrete quantities are substantially larger than those of other materials, concrete is shown separately from the remaining material categories.

In SFBs, timber frames are the most common. Nonetheless, concrete constitutes twice the mass of timber. The average single-family archetype used in this study contains approximately 400 kg concrete/m² GFA, compared with 200 kg/m² GFA reported by (Liu, 2025). The latter is based on a building representative of the 1990–2000 construction period, which may indicate that concrete use in foundations and ground slabs has increased over time. SFBs also exhibit substantial use of insulation, gypsum and plaster.

For MFBs, concrete is dominant, outweighing the combined mass of all other materials. In this study, each building archetype has a certain weighting factor that describes how many of that building archetype are built, which is also an important component when calculating average values. The weighted average concrete demand across all apartment-building archetypes is approximately 1,075 kg/m² GFA. However, substantial variation exists among recent studies. While the concrete-framed reference buildings underlying this study contain on average approximately 1,500 kg concrete/m² GFA, previous studies have reported values closer to 1,000 kg/m² GFA (Karlsson et al., 2021) (Erlandsson, et al., 2023), and as low as 600 kg/m²_{GFA} in (Liu, 2025).

For non-residential buildings, construction steel constitutes a comparatively large share of total material demand. This reflects the greater prevalence of steel-framed structures, which represent approximately 18–28% of non-residential buildings compared with only 0–2% of residential buildings (Malmqvist, 2023). It also reflects the extensive use of large steel-framed glass partitions in building types such as offices.



Figure 3. Material demands (kg/m² hfa) of new buildings built in year 2022, per building typology.

4.1.2. Material demand from new construction

To identify the building types contributing most to material demand, total material quantities for new construction in 2022 were assessed by building type (Figure 4).

The results confirm that concrete is the predominant material across all constructed buildings, with a notable dominance for residential buildings. Within the non-residential sector, offices represent a substantial portion of material demand. Notably, educational buildings and garages/ancillary structures also exhibit relatively high material intensities,

underscoring their significance despite smaller floor area shares. Targeted interventions in these categories could substantially influence national material consumption.

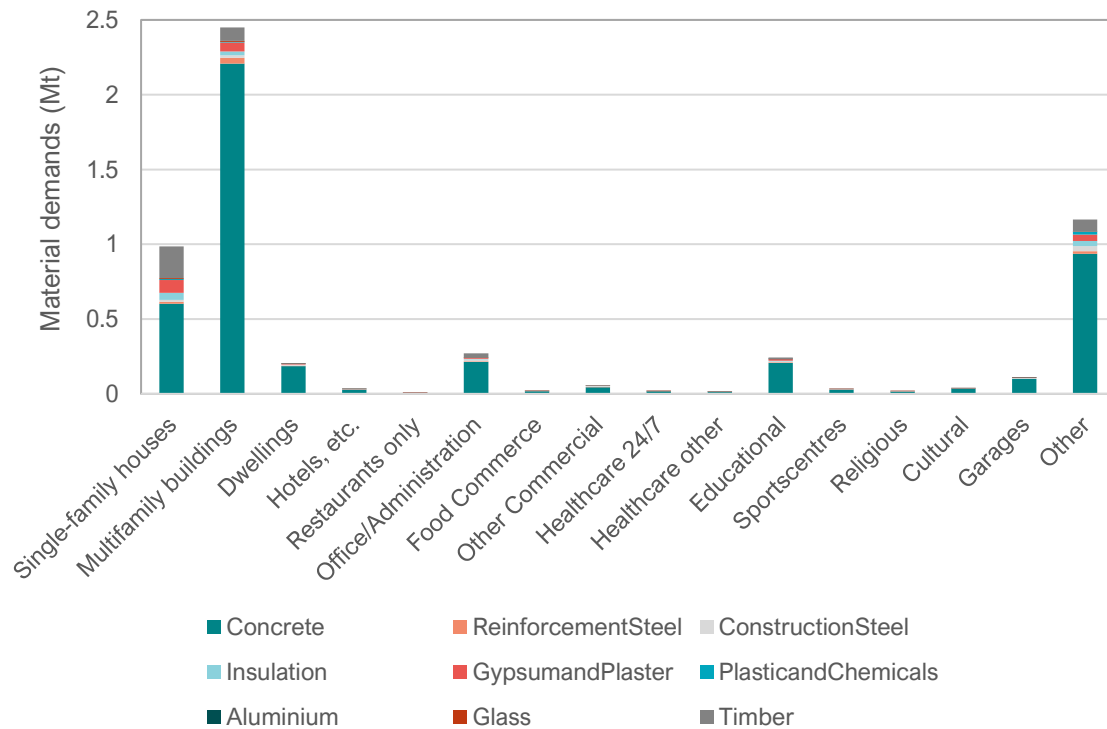


Figure 4. Material demands (Mt) of buildings constructed in 2022, per building type and material category.

4.1.3. Distribution across buildings elements

Figure 5 provides a breakdown of structural materials for new constructions in 2022 by building type, frame and building elements.

Concrete demand is concentrated in a relatively small number of building elements. Ground slabs represent a major share of concrete use across all building types and frame systems. In concrete-framed MFBs, walls constitute an additional major component and represent an area where hybrid timber-concrete structures may offer significant material savings (Pastori et al., 2022). For concrete framed non-residential buildings, joists and beams account for substantial concrete demand, while prefabricated concrete elements dominate in steel or timber framed buildings.

Steel demand consists of both reinforcement and construction steel. Reinforcement steel is distributed across several building types and building elements (Allwood, 2012). Structural steel demand is particularly significant in non-residential buildings, notably in steel-framed buildings and in pillars of concrete-framed structures. Although reinforcement steel dominates total steel demand, the results demonstrate that emissions-intensive structural steel components are also important contributors in non-residential buildings.

Timber use is most prominent in SFBs, where roofs and structural frames account for the largest shares. In other building types, timber is primarily associated with frame completion and secondary structural elements. Given the shorter replacement cycles of many of these

building elements, they may provide opportunities for increased circularity and material reuse.

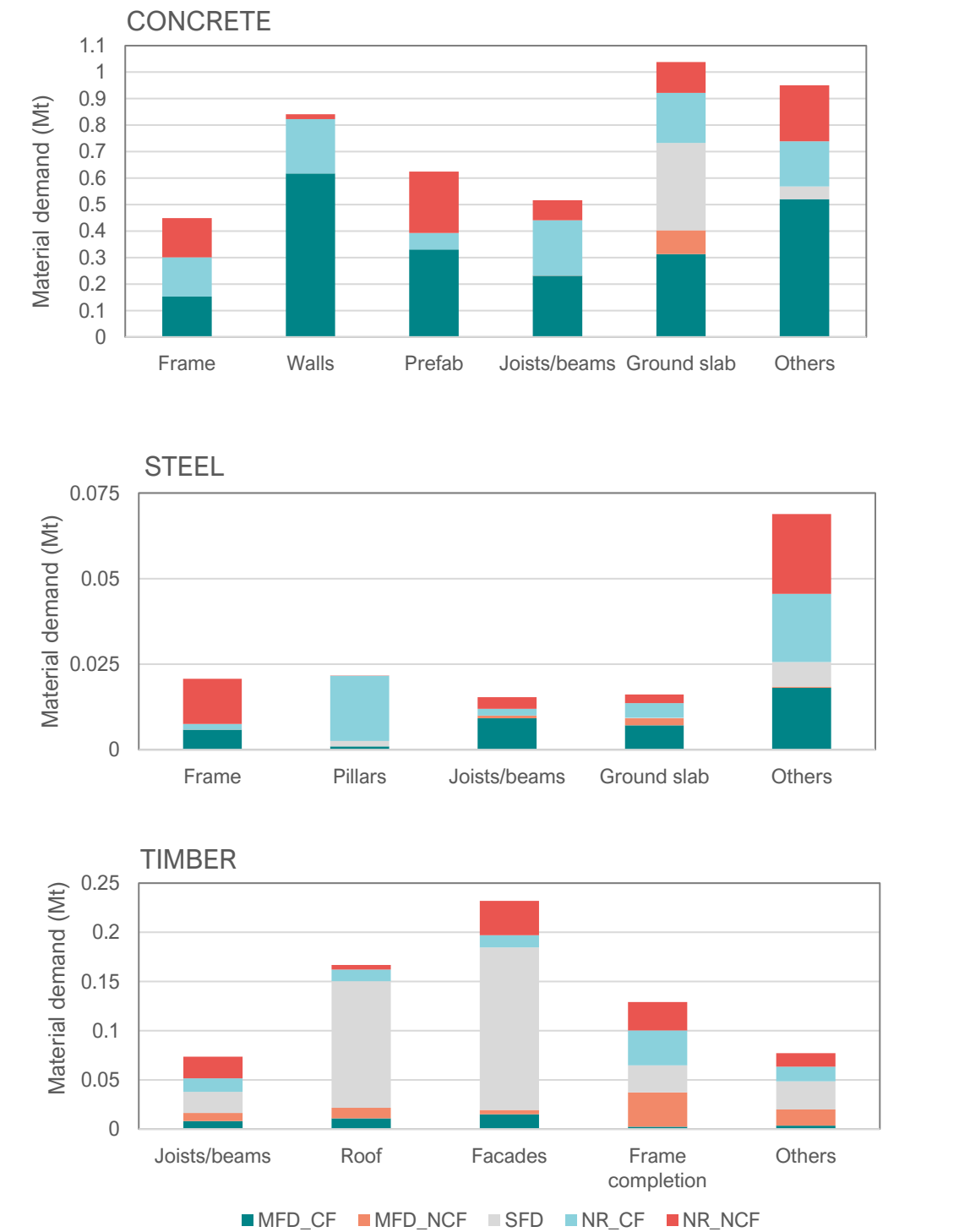


Figure 5. Concrete, steel and timber demand (Mt) of new buildings built in 2022, per building type and frame type (cf=concrete frame, ncf=non-concrete frame). Results are shown per building element for each building element with >10% of the total material demand. Note that the Unit of x-axis vary across the graphs.

4.2. Future demand for structural materials

Having established the current distribution of materials in new construction, the following section investigates how demand for key structural materials may evolve under different future development pathways.

4.2.1. Future material demand

Figure 6 presents the projected demand for major construction materials between 2022 and 2045 under the investigated scenarios. Across all scenarios, material demand remains relatively stable in the near term before gradually declining towards 2045, primarily due to slower population growth and a decreasing housing deficit after 2033 (Boverket, 2025b).

Concrete remains the dominant construction material throughout the study period, followed by timber, gypsum and plaster, insulation materials, and steel. The relative distribution between material categories changes only moderately over time, reflecting the continued importance of concrete-based structural systems in Swedish construction.

The material-efficiency pathways result in the largest reductions in material demand through optimized structural design, reduced material intensity, and increased use of hybrid structural solutions. In contrast, the electrification and CCS pathways primarily affect emissions from material production rather than material quantities.

Despite declining demand, substantial quantities of concrete, steel, and timber continue to be required in all scenarios, highlighting the importance of combining material-efficiency measures with low-carbon production technologies.

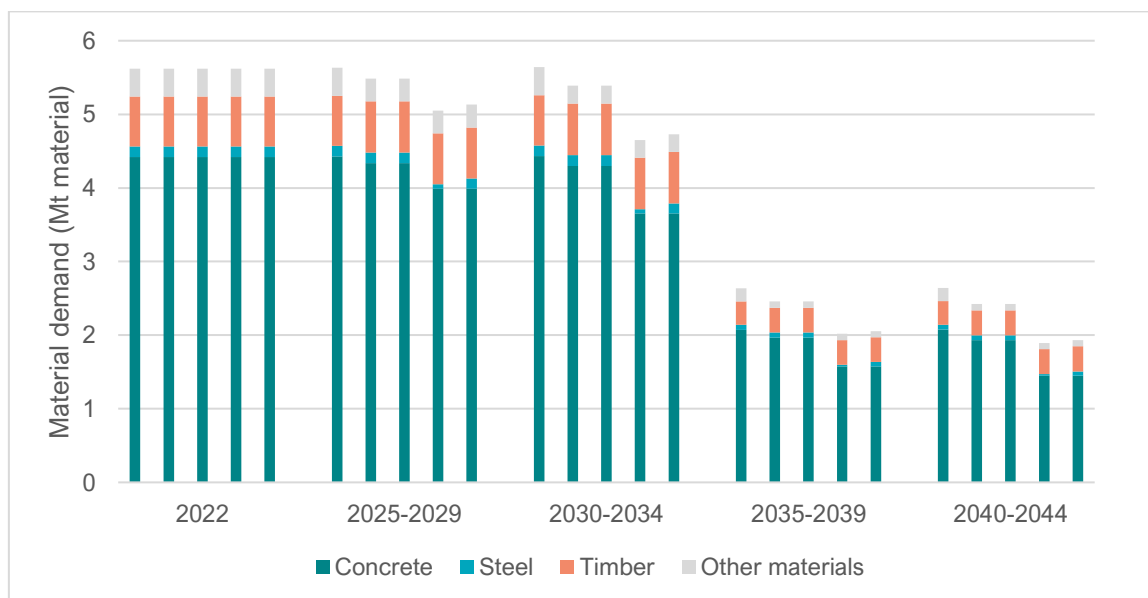


Figure 6. Projected demand for major construction materials in Sweden between 2022 and 2045 under the investigated scenarios. The BAU scenario is shown in the left-most bars for all time cohort, and the technology pathways 1 to 4 in succession towards the right-most bars.

4.2.2. Future concrete demand

Figure 7 presents the projected demand for concrete under the different scenarios. Concrete demand decreases across all scenarios due to lower construction volumes, with additional reductions in the material-efficiency pathways resulting from optimized structural design and increased use of timber and timber-concrete hybrid solutions. These reductions are most pronounced in multi-family and non-residential buildings, where opportunities for material substitution are greater.

The gap between the BAU and material-efficiency pathways widens over time, indicating that design optimization and material substitution can reduce concrete demand beyond the reductions achieved through declining construction activity alone. Nevertheless, concrete remains the dominant construction material throughout the study period in all scenarios.

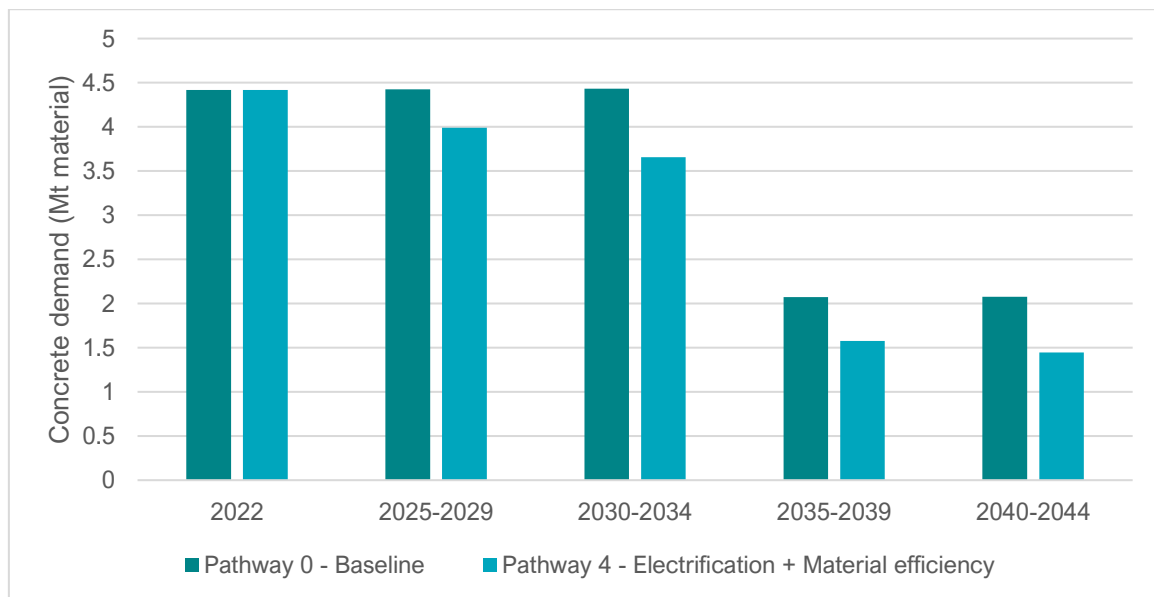


Figure 7. Total concrete demand (Mt) per year for new building construction in the analyzed construction periods. The figure shows the BAU pathway and one of the technological pathways implementing material efficiency measures, showing its effect on concrete demand.

4.3. Future WLC emissions

4.3.1. Emissions intensity of new construction

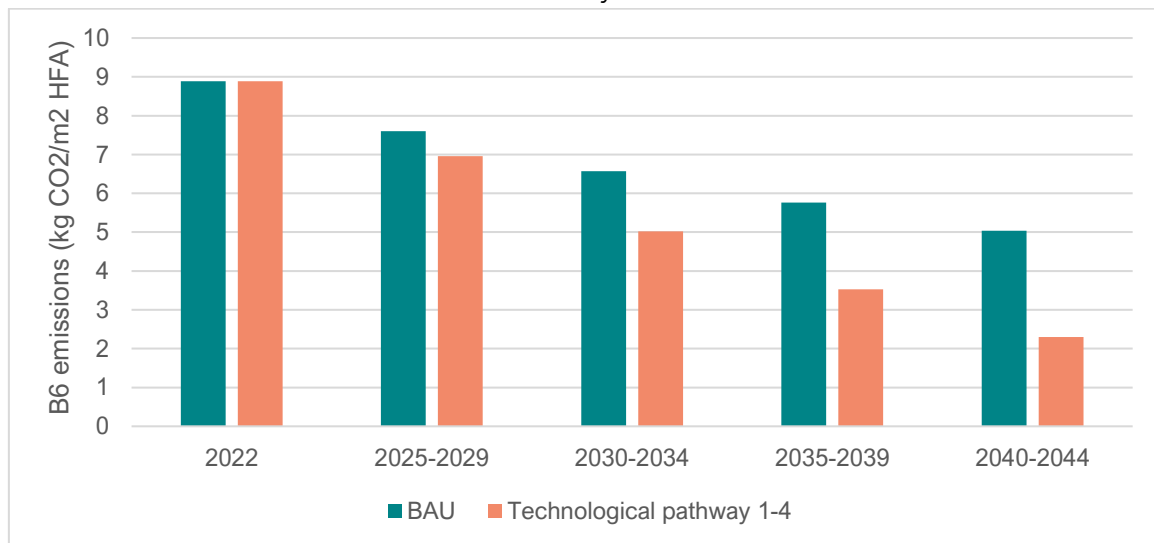


FIGURE 8 presents the GHG emissions intensity of newly constructed buildings for life-cycle stages A1–A5 and B6 under the business-as-usual (BAU) and mitigation pathways.

Embodied emissions from material production and construction (A1–A5) remain essentially unchanged in the BAU scenario, at approximately 320 kg CO₂e/m² HFA throughout the study period. In contrast, all mitigation pathways achieve substantial reductions. By 2030–2034, emissions decline to approximately 150–180 kg CO₂e/m² HFA, corresponding to reductions of around 40–55% compared with the baseline year. The differences between pathways become increasingly pronounced after 2030, reflecting the gradual implementation of industrial decarbonization technologies and material-efficiency measures. By 2040–2044, emissions fall below 100 kg CO₂e/m² HFA in all mitigation pathways, corresponding to reductions of 71–77% relative to the baseline. Pathway 4, combining electrification and material-efficiency measures, consistently yields the lowest emissions intensity, reaching approximately 75 kg CO₂e/m² HFA in 2040–2044. This indicates that combining low-carbon material production with reductions in material demand provides greater mitigation potential than either strategy alone.

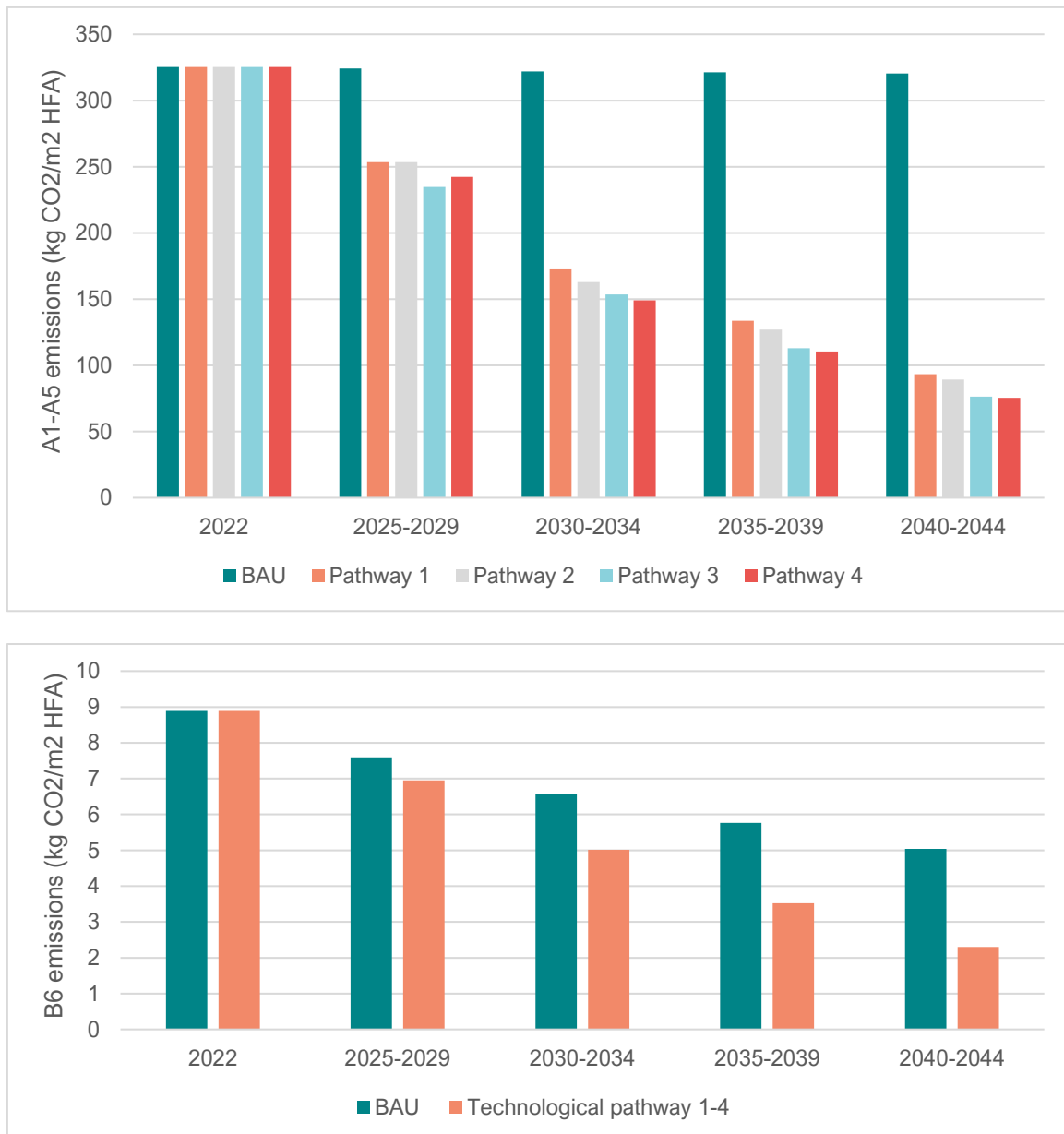


Figure 8. Projected annual embodied emissions (kg CO₂/m² HFA) from new construction (A1–A5) and operational emissions (B6) by scenario.

Operational emissions (B6) also decrease substantially over time. Under BAU, emissions decline from 8.9 kg CO₂e/m² HFA in 2022 to approximately 5.0 kg CO₂e/m² HFA in 2040–2044, reflecting the continued decarbonization of the Swedish energy system. In the mitigation pathways, operational emissions decrease further due to higher renovation rates and increasing deployment of photovoltaic systems. By 2040–2044, operational emissions reach approximately 2.4 kg CO₂e/m² HFA, corresponding to a reduction of almost 70% compared with the baseline year. The widening gap between the baseline and BAU and mitigation pathways over time highlights the increasing importance of electricity and district heating decarbonization, together with renovation measures, in reducing operational emissions. By 2040–2044, the mitigation pathways achieve approximately 50% lower B6 emissions than the BAU scenario.

The results indicate that substantial reductions in both embodied and operational emissions are technically achievable. However, the largest reductions are obtained when low-carbon material production is combined with material-efficiency measures, highlighting the importance of addressing both supply-side and demand-side drivers of emissions from the building sector.

4.3.2. National WLC emissions

While emissions intensities describe the performance of individual buildings, total sectoral emissions also depend on construction activity, renovation rates, and the size and performance of the existing building stock. Figure 9 therefore presents the projected annual emissions from the Swedish building sector across all life-cycle stages.

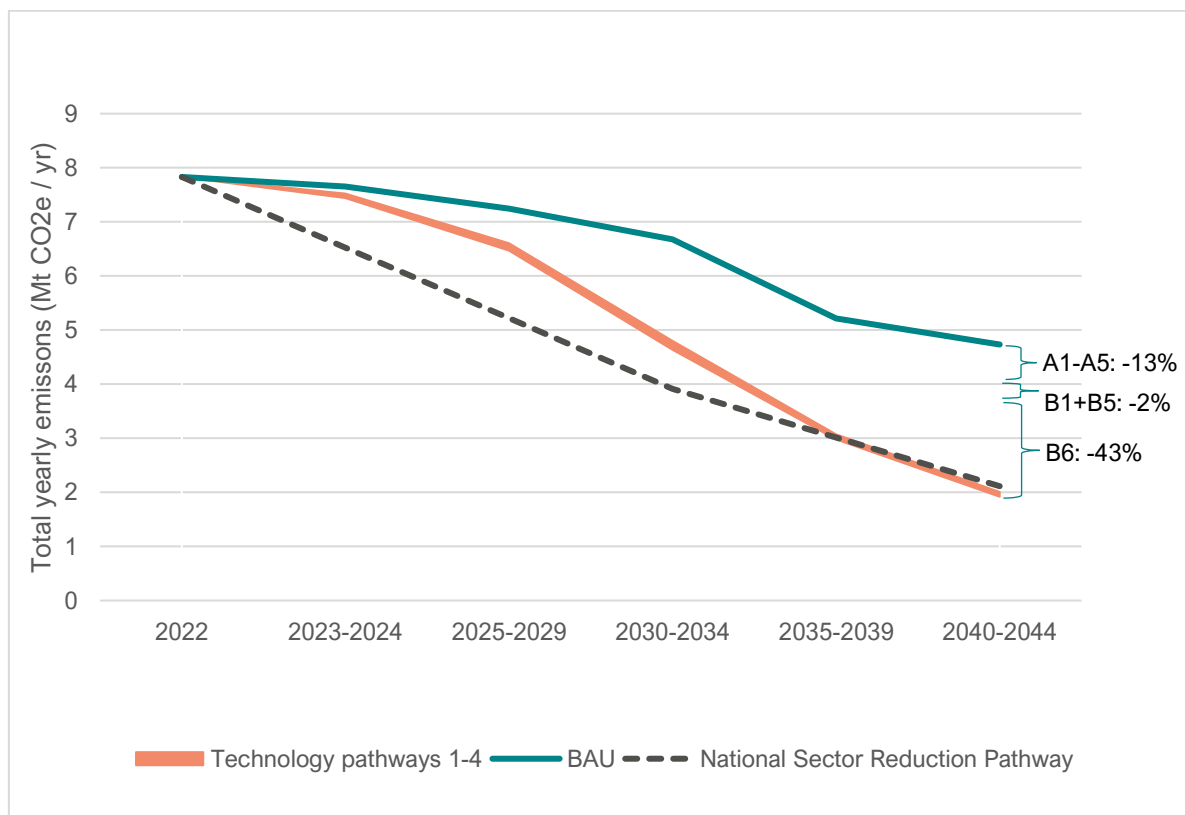


Figure 9. Annual whole-life-cycle emissions for the Swedish building sector by life-cycle phase and scenario, shown as five-year averages.

Under the BAU scenario, the total emissions decline only moderately from approximately 8 Mt CO₂/year in 2022 to 4.8 Mt CO₂/year by 2040–2044. In contrast, the combined mitigation pathways show a more substantial reduction down to 3 Mt CO₂/year by the end of the period. Additional emission reductions the BAU to the mitigation scenarios are primarily driven by phase B6 (operational energy use), which decreases by 43% compared to BAU, while phases A1–A5 and B1+B5 decrease by 13% and 2%, respectively.



Figure 10. Annual emissions by life-cycle phase for the investigated scenarios, shown as five-year averages. Emissions reductions from reduced emissions intensities of electricity and district heating used across lifecycles are shown as negative values.

Figure 10 further illustrates the contribution of individual life-cycle phases to the total emissions reductions achieved in the mitigation pathways compared with BAU. The results highlight that phase B6 remains the dominant contributor to total emissions across all periods. The B6 reduction potential from electrification and decarbonized energy supply is explicitly shown as negative values.

The remaining B6 emissions reduction stems from a combination of energy efficiency renovations, PV installations and behavioral changes reducing energy consumption across the entire building stock. While the PV installation rate does not alter between the scenarios, the energy consumption reductions follow the renovation rate. The embodied emissions associated with renovation measures correspond to 25 – 57 kgCO₂e/m² GFA being renovated. In the BAU scenario, the renovation rate of 1% result in embodied emissions linked to renovation of 0.25 MtCO₂e/yr. Operational emissions are reduced by around 0.1 MtCO₂e/yr (11 kgCO₂e/m²/yr renovated HFA), if not taking account of the energy system transition. The latter cumulates over time as a larger share of the building stock is renovated.

4.3.3. Comparison with national targets

To assess whether the investigated pathways are sufficient to achieve sectoral climate objectives, total emissions were compared with the reduction trajectory implied by the Swedish construction and real-estate sector roadmap, which targets a 50% reduction by 2030, a 75% reduction by 2040, and net-zero emissions by 2045.

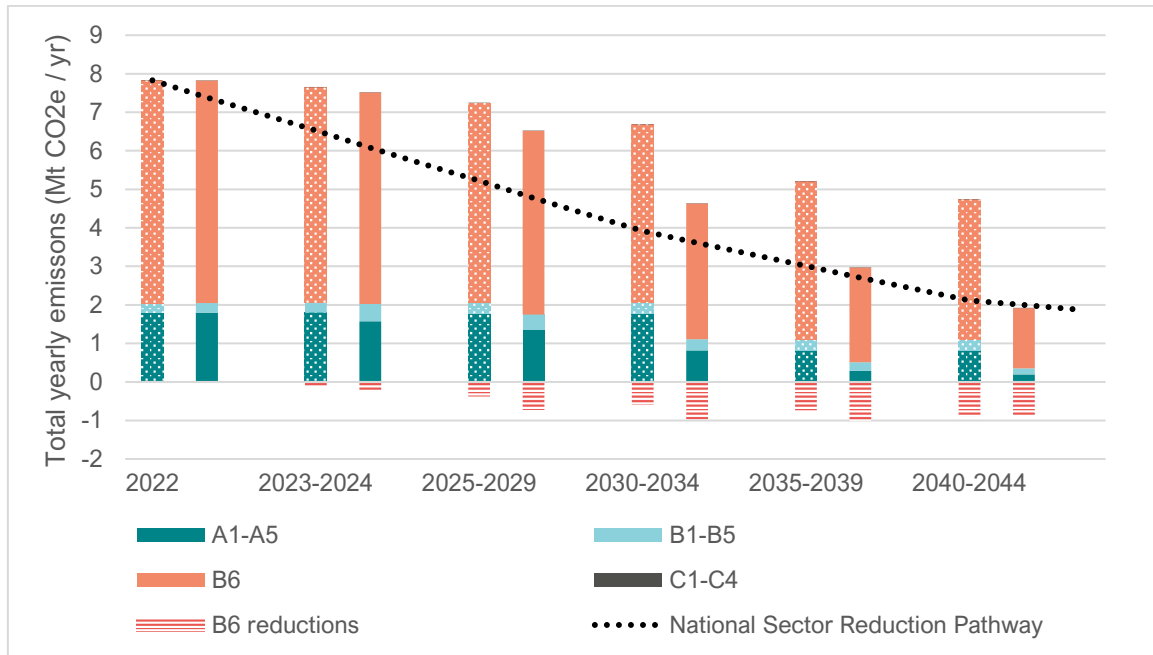


Figure 11. Total yearly emissions for life cycle phase A1-A5, B1+B5, B6 and C1-C4, over the construction period 2022-2044. The figure compares the BAU scenario, Technology pathway 4 and the emissions reduction targets from the National sectoral Fossil Free Sweden Roadmap.

Figure 11 presents the total emissions development under technology pathway 4, which includes electrification and material efficiency, compared to BAU. The mitigation pathway achieves consistent reductions across all life cycle phases, with a marked decline in B6 emissions. Notably, pathway 4 comes closest to meeting the national sectoral reduction pathway by 2040, although still slightly above target.

Overall, these results underscore the importance of targeted interventions in both embodied and operational emissions, with the greatest short- and medium-term impact achieved through energy system decarbonization and efficiency improvements in use-phase energy demand.

5. Discussion

Realizing the mitigation potential across life-cycle stages shown in this study requires coordinated shifts in decision-making and collaboration patterns. As we have shown, concrete is by far the material consumed the most in building construction. By breaking the concrete use down into the use in specific building elements, this study contributes to a better understanding of opportunities and challenges linked to development paths for efficient resource use and increased sustainability in the value chains for cement and concrete.

Material efficiency measures and recipe optimization linked to concrete use depend on early, cross-disciplinary collaboration among cement and concrete producers, structural engineers, contractors, and architects – beginning at concept design and continuing through procurement and construction phases (Walter P Moore, 2020). Real-world success depends on joint decision-making early in projects and aligned incentives throughout the process. While material efficiency measures can reduce material costs, they often entail higher transaction costs and perceived risks (Holmes, 2011; Mundaca et al., 2013). Enabling mechanisms include pain–gain sharing arrangements, collaborative procurement models, clear prioritization from top management, and allocation of sufficient time and competence for design iteration (Rootzén et

al., 2020). These arrangements help distribute risk and reward more equitably across the value chain, encouraging innovation and uptake of low-carbon solutions.

Structural system choices have a larger impact on embodied emissions. However, entrenched design cultures and regional building habits, rather than environmental performance, often determine structural system choices (Andersson et al., 2018). Shifting these norms through training, peer learning, and updated standards is essential for mainstreaming low-carbon practices. This cultural transformation must be supported by institutional frameworks that legitimize and prioritize sustainability goals. Normalizing renovation and refurbishment over new construction, adopting reuse-first strategies, and introducing carbon budgets per functional unit can steer upstream decisions with systemic impact (Kuittinen, 2023).

5.1. Methodological limitations and uncertainties

While the strength of our methodology is its novelty of combining archetype level LCA modelling with national stock dynamics, we acknowledge certain limitations in the stock description, dynamics and choice of scenarios.

To maintain computational feasibility, construction year was not included as a segmentation variable in the archetype modelling of phase A. Including this dimension would have increased the number of archetypes approximately tenfold. While this may mask some vintage-specific dynamics (explored e.g. in Gontia et al., 2019, 2018; Liu, 2025), it does not alter the central conclusions.

Data uncertainties in stock description, such as discrepancies between Statistics Sweden and Swedish Energy Agency, required synthesizing building, dwelling, and heated floor area datasets. Similar issues challenges were encountered for non-residential stocks. Uncertainties in stock characterization are particularly evident for the baseline year 2022, where discrepancies in new construction data influence the estimated balance between emissions from new construction and the existing building stock. Consequently, embodied emissions associated with new construction are likely underestimated relative to emissions associated with the existing stock.

The underlying archetype data used in this study includes the foundation, load bearing structural frame, roof, facades, non-load bearing elements. We note however that other building elements (technical installations, interior finishes and fixed furnishings) may contribute around 20% of total embodied emissions depending on the building type (34-81 kgCO₂e/m² GFA according to (Malmqvist et al., 2023)). For renovations, these building elements contribute to a larger share of embodied emissions, constituting on average 34 kgCO₂e/m² GFA, i.e. 35 % of overall renovation emissions. As these building elements are not included in this study, the embodied emissions of new construction as well as renovations are underestimated, and embodied renovation emissions linked to repair and replacement B2-B4 are not fully captured.

The assessment of renovation-related embodied emissions is associated with particularly high uncertainty, as it's simplified as a constant. Existing literature reports substantial variation in system boundaries, renovation scope, material requirements and resulting energy savings (Zimmermann et al., 2023).

Additional uncertainty is associated with the projection of future building-stock developments. Due to a lack of alternative data sources, projections used building permits as a proxy for near-term trends, despite their limitations for long-term forecasting. Future shares of PV and ventilation measures along with material data for large-area archetypes such as industrial buildings and warehouses drew on limited, partly expert-judged datasets. Lastly, future non-residential construction demand is modelled to follow residential trends, without accounting for

sector-specific dynamics, which may reduce the accuracy of projections for non-residential building types. While these uncertainties influence absolute values, they are unlikely to change the direction of value-chain effects.

5.2. Carbon uptake and biogenic carbon accounting

The potential for carbonation in concrete during the use phase (B1) was included using the standard sequestration rate proposed by (IVL, 2024) corresponding to approximately 1–3% of the A1–A3 emissions from concrete. However, carbonation rates depend on factors including structural design, exposed surface area, cement composition and building lifetime. Previous studies indicate that up to approximately 20% of the original concrete carbon footprint may be reabsorbed under favourable conditions (Selander et al., 2022). Additional carbonation during demolition and concrete crushing was not considered in this study but may represent further mitigation potential.

In accordance with current O/O accounting practice and prevailing standards (Erlandsson et al., 2024; ISO, 2020), biogenic carbon uptake in wood products was not included. However, this remains an active area of methodological development, and ongoing discussions within the European Union may lead to revised approaches in future regulations and certification frameworks (European Commission, 2025a, 2025b).

5.3. Further research

Several opportunities exist to further develop the modelling framework. First, future versions should incorporate technical installations, interior building elements and repair and replacement activities to improve completeness of embodied emission estimates. Second, behavioural and sufficiency-oriented scenarios should be introduced to evaluate the influence of floor area demand, occupancy rates and building reuse on future emissions. Third, optimization approaches could be integrated to identify cost-effective stock transformation pathways and prioritize renovation measures across the building stock. Finally, future work should explore interactions between building-sector measures and broader industrial decarbonization strategies, including circular material flows, reuse systems and carbon removal technologies.

6. Conclusions

This study presents a novel and validated modelling framework that integrates detailed building typologies with life cycle-based scenario development, combining socioeconomic and technological drivers. The approach, applicable beyond Sweden, enables national-scale assessments of material demand and GHG emissions from new construction, supporting forward-looking analyses aligned with climate and resource efficiency goals.

By mapping material use across building elements, typologies, and frame types, the model provides a detailed allocation of structural materials throughout the building stock. The results reveal that concrete dominates overall material demand, particularly in load-bearing elements such as ground slabs and walls in multi-family and non-residential buildings. Steel use, beyond reinforcement, is also significant in non-residential structures, especially in pillars and structural frames. Timber use is concentrated in single-family buildings (SFB), reflecting current building practices. Still, the general trend in the sector is toward taller, more material-intensive buildings.

Future scenario analysis highlights that declining population growth and slowing construction activity are likely to reduce total material demand. Nevertheless, material

efficiency measures, such as structural optimization, material substitution, and material production transitions offer substantial additional emission reduction potential in both the short and long term. These findings underscore the importance of integrating material demand strategies into national decarbonization pathways, complementing efforts already underway in sectoral roadmaps and industrial transformation initiatives.

Importantly, none of the investigated pathways – despite combining technological improvements and material efficiency – fully achieve Sweden’s long-term climate targets for the building sector. This indicates that deeper structural changes may be necessary, including shifts in consumption patterns, more radical circularity strategies, and stricter policy instruments to limit emissions from both material production and construction practices.

Our study advances the methodological state of the art by combining archetype-level LCA with national stock dynamics to map the distribution of construction materials across building types and components. This integration strengthens system understanding and enables scenario exploration at scales relevant to policy and industry decision-making. At the same time, the results, together with our methodological choices and limitations, point to a central conclusion: technological options are already sufficient to deliver large near-term emission reductions, but their realization depends on coordinated behavioral and organizational changes across the value chain.

Appendix

Table A1. Validation of the quantification: Total number of buildings and heated floor areas (HFAs) in the model, compared to available estimates from the literature given among brackets [percentage: results divided by literature], by building subsector. All sources are given in the table.

Building subsector	Number of buildings [%]				HFA (Million m ²) [%]			
	Before 2005	2006-21	2022	Total existing stock 2022	Before 2005	2006-21	2022	Total existing stock 2022
SFB	1 887 666 [102%] ³	151 158 [95%] ³	10 417 [122%] ^{3,2}	2 049 142 [102%]	301.15 [104%] ⁷	19.49 [74%]	1.34 [340%] ⁷	320.65 [101%]
MFB	165 828 [n.a.]	11 173 [n.a.]	336 [n.a.]	177 337 [n.a.]	236.57 [126%]	21.34 [71%]	1.82 [26%]	257.91 [118%]
Total Residential	2 053 395 [n.a.]	162 331 [n.a.]	10 753 [n.a.]	2 226 479 [n.a.]	537.72 [112%]	408.47 [73%]	3.16 [44%]	578.57 [108%]
Special dwellings	6 106 [100%]	0	295 [40%]	6 401	3.10 [100%]	0	0.28 [n.a.]	3.10 [89%]
Hotels	6 682 [100%]	842 [137%]	49 [3%]	7 574 [86%]	7.30 [100%]	0.85 [82%]	0.05 [n.a.]	8.15 [98%]
Restaurants	4 014 [100%]	917 [211%]	29 [2%]	4 960 [85%]	1.80 [97%]	0.39 [134%]	0.01 [n.a.]	2.18 [102%]
Office/ Administration	16 051 [100%]	1 573 [123%]	141 [6%]	17 766 [91%]	28.10 [100%]	2.97 [88%]	0.30 [n.a.]	31.07 [99%]
Food commerce	3 379 [100%]	0	16 [2%]	3 395	4.30 [99%]	0 [100%]	0.03 [n.a.]	4.30 [87%]
Other commercial	7 208 [100%]	288 [54%]	57 [4%]	7 553 [81%]	10.40 [100%]	0.50 [29%]	0.11 [n.a.]	10.89 [90%]
Healthcare 24/7	3 161 [100%]	1 944 [549%]	8 [-6%]	5 113 [151%]	13.10 [100%]	7.57 [283%]	0.03 [n.a.]	20.67 [131%]
Healthcare other	2 928 [100%]	534 [154%]	14 [1%]	3 476 [67%]	3.90 [100%]	0.78 [105%]	0.02 [n.a.]	4.67 [101%]
Educational	17 553 [100%]	1 569 [105%]	97 [4%]	19 219 [90%]	40.49 [100%]	3.60 [67%]	0.21 [n.a.]	44.09 [96%]

Sports centers	2 973 [100%]	1 434 [362%]	27 [1%]	4 433 [86%]	5.10 [99%]	2.67 [253%]	0.05 [n.a.]	7.77 [125%]
Religious	3 689 [100%]	729 [296%]	46 [-4%]	4 464 [158%]	2.00 [101%]	0.38 [200%]	0.02 [n.a.]	2.38 [110%]
Cultural	3 218 [100%]	127 [46%]	49 [5%]	3 394 [74%]	2.30 [98%]	0.13 [34%]	0.05 [n.a.]	2.42 [89%]
Garages	2 624 [100%]	472 [231%]	152 [26%]	3 248 [95%]	1.60 [100%]	0.45 [98%]	0.15 [n.a.]	2.04 [99%]
Other	8 932 [100%]	885 [155%] ⁵	685 [-36%] ⁵	10 502 [139%]	13.10 [100%]	1.40 [116%]	1.04 [n.a.]	14.50 [101%]
Total Non Residential	88 518 [100%] ¹	11 315 [154%]	1 664 [13%] ⁸	10 1497 [94%]	136.56 [100%] ¹	19.52 [111%] ⁵	2.35 [n.a.]	158.29 [101%]

¹(Energimyndigheten, 2011), ²(Energimyndigheten, 2022), ³(Energimyndigheten, 2023a), ⁴(Energimyndigheten, 2023b), ⁵(Energimyndigheten, 2023d), ⁶(Energimyndigheten, 2023e), ⁷(Energimyndigheten, 2023f) ⁸ (Energimyndigheten, 2020)

Table A2. Validation of the quantification: Total number of Dwellings in the model, compared to available estimates from the literature given among brackets [percentage: results divided by literature], by building subsector. All sources are given in the table.

Building subsector	Before 2005	2006-21	2022	Total existing stock 2022
SFB ⁹	1 981 945 [102%]	151 746 [99%]	10 460 [107%]	2 144 151 [101%]
MFB	2 838 959 [124%]	344 089 [113%]	22 738 [56%]	3 205 785 [121%]
Total R dwellings	6 452 953 [113%]	495 834 [108%]	33 198 [66%]	6 981 985 [112%]

⁹(SCB, 2025c)

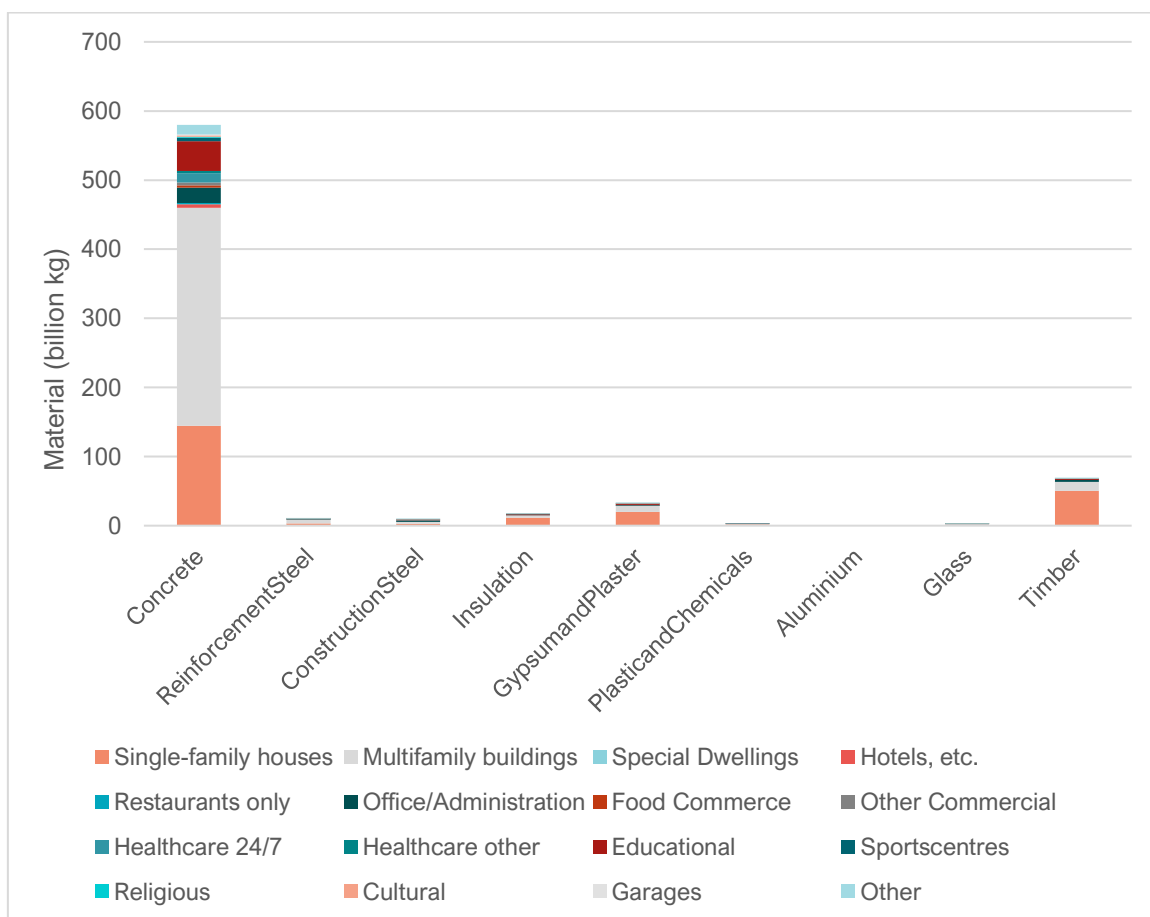


Figure A1. Cumulative material stock in buildings constructed before 2023, disaggregated by building type and material category. The figure illustrates the estimated amounts of construction

materials in the existing building stock. Results are based on archetype mapping and underlying data sources used in this study.

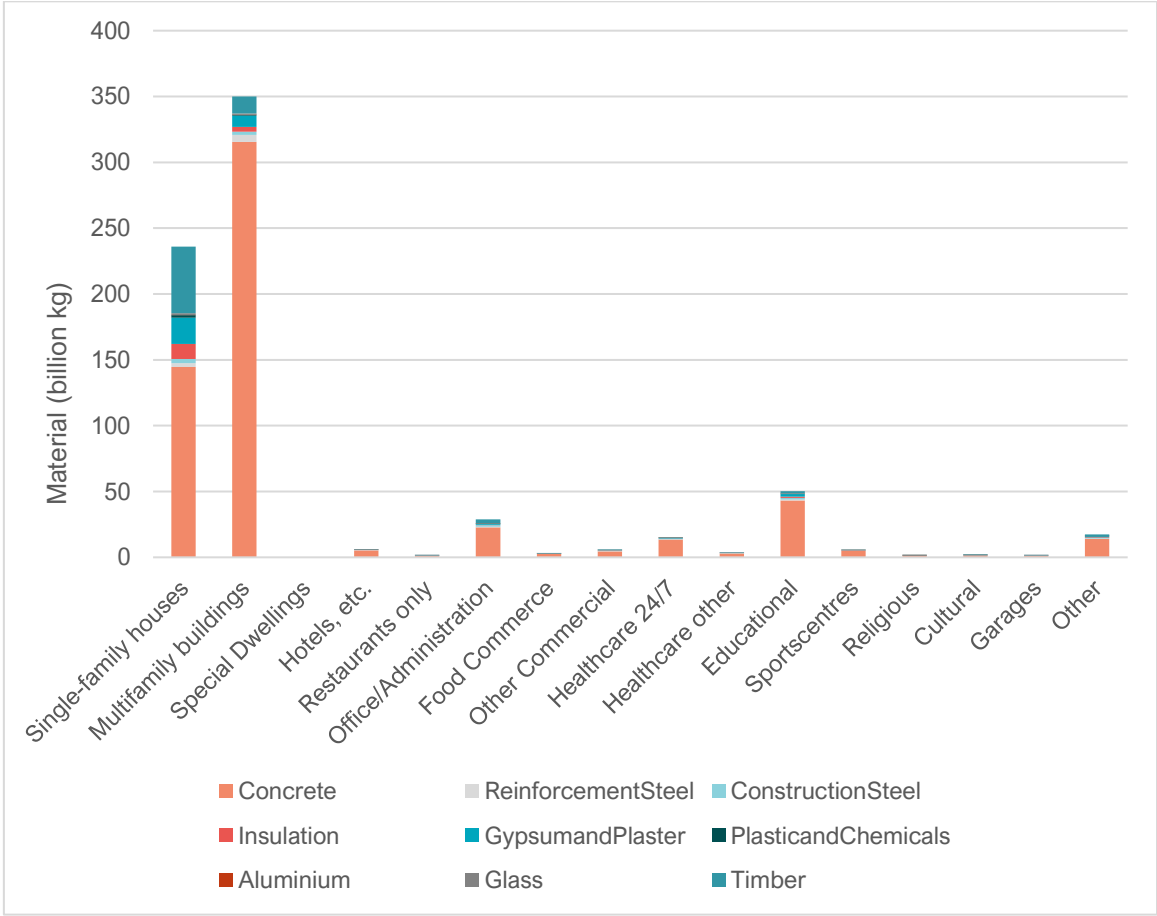


Figure A2. Distribution of cumulative material stock in buildings constructed before 2023 across building types. The figure provides a breakdown of the existing material stock by building typology, highlighting differences in material composition and volume.

Supplementary materials

SM1_Climate impact. Climate impact (A1-A5) for reference buildings and a comparison between model calculations and Boverket data used for validation.

SM2_Material demand Material demand per resource group (kg) generated per building archetype.

SM3_Energy Average U-values and primary energy performance by building type and construction period.

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- Energimyndigheten, 2025c. Nätanslutna solcellsanläggningar.
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- Energimyndigheten, 2023b. Table 3.1 Number of dwellings in multi-dwelling buildings in 2022, by type of heating system used, year of completion, type of ownership and dimensions, 1 000s.
- Energimyndigheten, 2023c. Table 2.4 Average use of energy for heating and hot water for district heating per square meter in non-residential premises 2009-2022, by year of completion, kWh/m².
- Energimyndigheten, 2023d. Table 3.2 Number of non-residential properties in 2022, by type of heating-system used and type of premise.
- Energimyndigheten, 2023e. Table 3.4 Heated residential and non-residential area of non-residential premises in 2022. by type of heating-system used and type of premise. <https://doi.org/https://www.energimyndigheten.se/statistik/officiell-energistatistik/tillforsel-och-anvandning/energistatistik-for-lokaler/?currentTab=0>
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- Energimyndigheten, 2022. Table 3.1 Number of one- and two-dwelling buildings in 2021, by year of completion, type of heating system used and size, 1 000s.
- Energimyndigheten, 2020. Table 3.1 Number of buildings with non-residential properties in 2019, by type of heating-system used, year of completion, type of ownership and size of area, 1 000s.
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