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Emissions Accounting for Germany's Construction and Real Estate Industry: Basics, Current Status, and Needs

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Abstract.
A global carbon budget, as defined by the IPCC, is derived by subtracting the emissions released since 1850 from total permissible emissions, based on the Paris Agreement's 1.5°C target. The IPCC's global reduction pathway defines the required emissions reductions and their timeline. However, translating this budget into national and sectoral targets is challenging due to country-specific differences and methodological uncertainties. For example, most studies and statistics in Germany are based on the Climate Protection Act (KSG), which only accounts for direct emissions in relation to specific sectors. As a result, there is no uniform and cross-sectoral system boundary for the German construction and real estate industry, which includes direct and indirect emissions as well as embodied emissions.
This contribution develops an integrative approach combining top-down and bottom-up methods to identify gaps in existing statistics and studies that primarily focus on the KSG-defined building sector. The top-down approach applies macroeconomic data and multiregional input-output (MRIO) models to quantify consumption-based emissions and cross-sectoral linkages. The bottom-up approach combines disaggregated life cycle data from environmental product declarations (EPDs) for construction products and processes and national production statistics to assess material- and activity-specific emissions along the entire building life cycle. Simultaneously, identified gaps in the opening balance and emissions trajectories are addressed by integrating disaggregated bottom-up data into the overarching top-down structure. The objective is to develop a hybrid conceptual model that bridges both approaches and enables a harmonized, phase-specific attribution of greenhouse gas emissions. This paper focuses on a conceptual approach rather than presenting quantitative results. It supports German authorities in closing gaps in national statistics and regulation. The outcome demonstrates how emissions should be quantified to define a reduction pathway for the construction and real estate industry in accordance with the requirements of the European Energy Performance of Buildings Directive (EPBD) and guiding future integration into dynamic, scenario-based modelling to support compliance with carbon budgets.

1. Introduction

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To limit global warming to 1.5°C, a carbon budget defines the maximum allowable GHG emissions, quantified in CO_2-equivalents (CO_2eq.) using the GWP100 metric [1]. Effective mitigation requires a structured, science-based pathway, particularly for high-emission sectors like construction and real estate, one of Germany's largest contributors [2]. To comprehensively assess emissions in this sector, two methodological approaches can be distinguished: a macroeconomic top-down approach and a building-specific bottom-up approach. Meeting climate targets requires not only defining reduction goals but also assessing their feasibility within the existing building stock from a bottom-up perspective with building-, product-, and material-specific analyses to identify reduction potentials. The European Energy Performance of Buildings Directive (EPBD) mandates zero-emission new buildings in operation by 2030 and a climate-neutral EU building stock by 2050, emphasizing the need to consider both embodied and operational emissions. The central question this paper seeks to answer is: *How can top-down and bottom-up approaches be integrated to enable cross-sectoral carbon accounting in the German construction and building industry?*

To answer this question, Chapter 2 explores existing methodological and systemic gaps in emission quantification, while Chapter 3 develops a hybrid conceptual framework for evaluating emissions in the German construction and real estate industry, drawing on both national and international best practices. Such an integrated methodology is essential for defining a consistent starting point for carbon accounting, tracking progress and supporting institutions, such as statistical offices, regulatory agencies, and research organizations, in generating emission inventories and ensuring adherence to climate budgets.

2. Limitations of existing top-down and bottom-up approaches

Initial studies indicate that the Paris Agreement's 1.5°C target may be missed within four years [3] or has already been exceeded [4]. From 2023, the remaining global CO_2 budget (50% probability) is 380 Gt CO_2 [5]. Although such budgets have been established, they are not legally allocated either nationally or to individual sectors. The German Advisory Council on the Environment (SRU), for instance, proposes a 4.8 Gt CO_2 national budget for a 1.75°C pathway (67% probability), covering emissions until 2037 [6]. However, there is neither a sector-specific carbon budget nor a consistent definition of the construction and building sector, and cross-sectoral integration remains ambiguous. A literature review of national and international studies shows that differences in results stem mainly from varying system boundaries and life cycle coverage (see Table 1).

Table 1. Opening Balance Adjusted to the Chosen Definition

Opening Balance	"Sector Buildings" [7]	"Field of Need Housing" [8]	"Field of action: Construction & Use of Buildings" [2]	Economic Sector [9]
year	2021	2020	2014	2008
(Mt CO_2-eq.)	119.5	198	364	472
%	16	27	40	48

National statistics and studies using the "Sector Buildings" [10] solely follow a top-down approach focus on direct emissions within national borders, following the source principle, which attributes emissions to their place of origin [11]. They include both residential and non-residential buildings. Key policies like the Buildings Energy Act (GEG) and the Federal Funding for Efficient Buildings (BEG) target operational emissions but ignore embodied emissions from construction and renovation.

The "Area of Need Housing" primarily focuses on direct and indirect emissions arising from energy consumption in households [8]. This includes emissions from space heating, hot water preparation, and electricity generation for household use. It primarily accounts for operational emissions caused by energy consumption but excludes upstream embodied emissions from the production, transportation, and maintenance of buildings and materials [8, 10, 12].

The hybrid approach publicated by BBSR [2] serves as a key example of a hybrid method that combines top-down and bottom-up approaches, adopts a consumption-based perspective, and applies the polluter-pays principle. This approach offers a comprehensive perspective and is aligned with the "Field of Action: Construction and Use of Buildings" [2], which explicitly integrates both residential and non-residential buildings. Emissions are attributed to their point of physical release, based on the consumption of products, goods, and services. The top-down approach uses a multiregional input-output model (MRIO) [2], which is suitable for Germany, where consumption-based emissions exceed production-based ones by 20%, and only half of GHG emissions occur domestically [13]. The MRIO model links construction statistics and trade data to quantify production in the construction sector, covering upstream and operational stages while excluding end-of-life phases [14]. The operational emissions are estimated based on a combination of national end-energy consumption statistics and the KBOB life cycle assessment database [15].

Additionally, the hybrid approach of [9] analyses the construction and real estate industry by economic sectors, corresponding to the statistical classification in the European Union (NACE), which aligns with the internationally recognized ISIC classification [16]. Unlike the MRIO, this approach considers imports and exports only to a limited extent and captures the industry, without distinguishing between building types or infrastructure [9]. The bottom-up approach links economic sectors with EPDs, Ökobaudat [17], and German production statistics to estimate cradle-to-gate GHG emissions of construction materials within an environmental-economic accounting framework. End-of-Life datasets were not considered in the analysis.

The differences in system boundaries highlight the need for a regulatory framework to address cross-sectoral emission overlaps holistically [18]. Rheude and Röder [19] extend the approach by Volk [9] by incorporating import and export data into the top-down estimation of material consumption. Their bottom-up approach focuses on materials relevant to the structural framework and includes partial allocation based on market analysis, without differentiating between building types or construction activities. Table 1 shows that emission levels differ markedly depending on the definition applied: the "economic industry" category captures the highest share due to broad, cross-sectoral boundaries including embodied emissions, while the "area of need housing" reflects the lowest share, limited to operational household energy use.

Besides the previously discussed hybrid approaches, international examples such as Giesekam et al. [20] and O'Hegarty & Kinnane [21], also apply a cross-sectoral perspective and offer important input for their further advancement. The UK Buildings Embodied Carbon (UK BIEC) model by Giesekam et al. [20] integrates a MRIO model to estimate embodied emissions at the sectoral level and a bottom-up LCA database covering ten building types. For each type, carbon intensity and output functions are derived to project historical and future construction activity. Bottom-up results are calibrated against MRIO-based top-down data, with discrepancies redistributed proportionally across building categories. Scenario analyses are an important setup beyond static models like Volk and BBSR [2, 9], highlighting the construction sector's high sensitivity to dynamic developments. O'Hegarty & Kinnane [21] present a scalable hybrid framework aligned with DIN EN 15978:2012-10 [22] covering both operational and embodied emissions across all life cycle stages. Table 2 compares the respective methods.

Table 2. Methodological Overview of GHG Quantification Models (Key Focus and Identified Gaps)

	Source	DIN EN 15978	Key Focus & Characteristics	Identified Gaps
Hybrid	Rheude & Röder (2022)[19]	A1–A3	Top-down: MRIO; bottom-up: structural framework materials. Cradle to gate	No A4-A5, B6-7, C1-C4, D no building type differentiation
	O'Hegarty & Kinnane (2022) [21]	A1–A3, A4-A5, B1–B6, C1-C4	Scalable hybrid framework, scenario analysis. Operational and embodied emisions	Excludes Module D
	BBSR (2020) [2]	A4-A5, B4, B6	MRIO + Ökobaudat + KBOB data; Operational and embodied emissions	A1-A3 not detailed Excludes C1-C4, D
	Giesekam et al. (2018) [20]	A1–A5, B1–B7, C	MRIO + LCA for building types; scenario analysis	Excludes Module D
	Volk (2011)[9]	A1–A3, A4-A5, B6, C1-C4	Top-down: production statistics, bottom-up: Embodied emissions (cradle-to-gate)	No Module D No import and export data
Top-down	National Statistics [8, 23]	B6.1 (KSG); B6.1, B6.2, B6.3 (Field of Need)	Operational emissions within national borders	No embodied emissions
	REMod-D (2018) [24]	B6	Building stock treated as aggregated energy consumer	No A1–A5; C; D
Bottom-up	SLiCE (2024) [25]	A1–A3, A4–A5, C1–C4, D	Embodied emissions from material flows and circular economy; dynamic LCA	No B6–B7
	Invert/EE-Lab (2015) [26]	B6–B7	Technology diffusion, user behavior modelling, scenario analysis	No A1–A5, C1-C4, D
	AWOHM (2014) [27]	B6	Agent-based model; decision-making of households	No A1–A5, C1-C4, D
	OTELLO (2011) [28]	A1–A5, C1–C4, B6–B7	Operational + embodied emissions: decarbonization scenarios	No actor-level modelling

While the existing approaches mainly provide static solutions, dynamic models can address these gaps through scenario-based, actor-sensitive, and life cycle-integrated analyses (see Table 2). A key dimension in evaluating the modelling approaches lies in their coverage of life cycle phases as defined by DIN EN 15978 [22]. The German building stock is assessed using diverse models that vary in temporal scope, building typologies, and life cycle coverage. SLiCE [25] focuses on embodied emissions from materials, construction, and disposal, based on Ökobaudat [17] and national statistics, but omits operational energy. Invert/EE-Lab [26] and REMod-D [24] simulate energy use and GHG emissions during operation, excluding embodied emissions. OTELLO [28] integrates both embodied and operational emissions, modelling renovations and efficiency improvements, while AWOHM [27] captures behavioural dynamics in retrofit decisions but excludes material and end-of-life emissions. The following framework builds on static and hybrid approaches (BBSR [2], Volk [9], Rheude & Röder [19]) as a baseline for quantifying current GHG contributions, which future research should expand through dynamic and scenario-based modelling.

3 Linking Top-Down and Bottom-Up Approaches

3.1 Analytical Scope of the Conceptual Framework

Building on existing approaches, the best elements of the models discussed in Chapter 2 were combined to develop a hybrid methodology, which is illustrated in Figure 1.

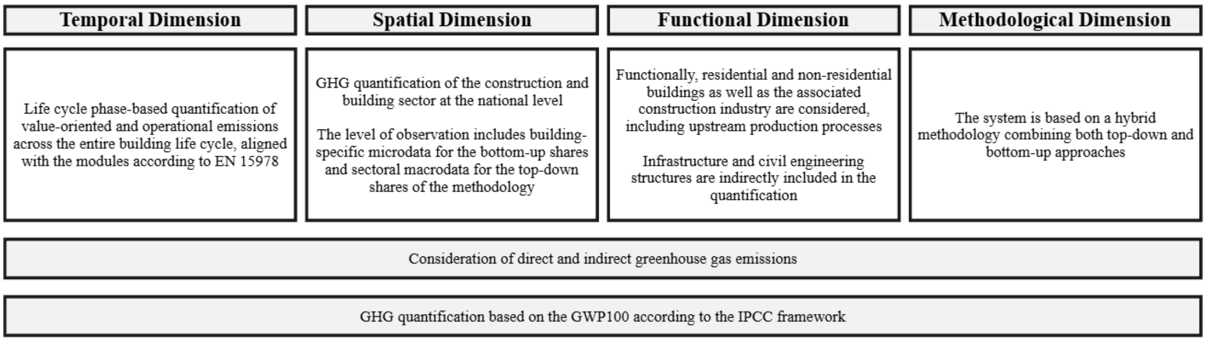

Figure 1. Definition of the conceptual framework of the hybrid GHG quantification in the construction and real estate industry based on [29]

The framework aims to quantify GHG emissions of the construction and real estate industry in a cross-sectoral, life cycle-based, and cause-specific manner. It builds on the LCA categorization by Teng et al. [29] and expands it with additional specifications. Originally developed for LCA, their structure is adapted here to allocate emissions to the specific life cycle phases in which they occur, instead of averaging them over the building lifetime [30].This approach highlights temporally concentrated emission peaks, particularly during construction and renovation. From a spatial perspective, the framework enables national-level GHG quantification by linking disaggregated material data with macroeconomic sector and trade statistics. This allows regulatory and statistical institutions to generate harmonized, consistent inventories aligned with national and international climate targets. It covers both residential and non-residential buildings, including related construction activities and upstream processes. Infrastructure is indirectly included via industry-level and energy consumption data. By combining bottom-up and top-down methods, the framework establishes a coherent accounting structure connecting macroeconomic interdependencies with building-specific data.

3.2 Structure of the Conceptual Framework

Figure 2 provides a more detailed representation of the hybrid approach, developed by authors:

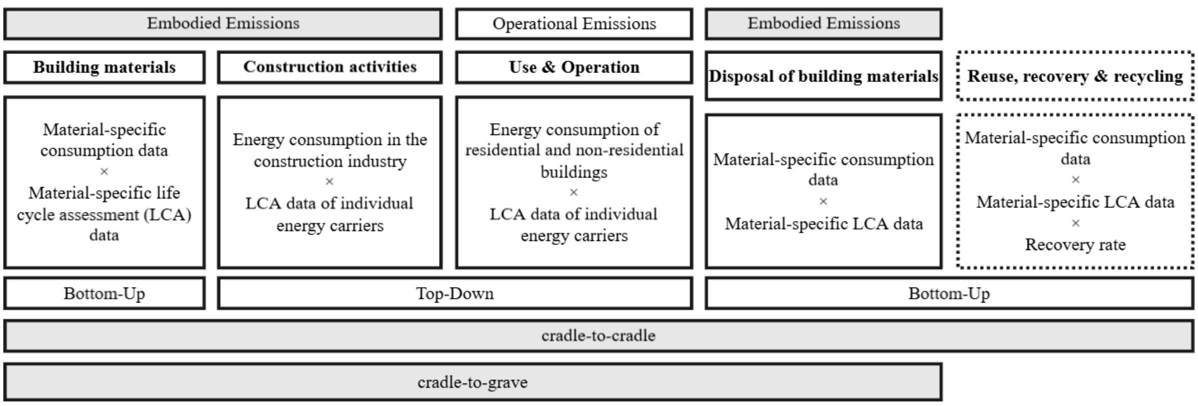

Figure 2. Detailed Conceptual Framework

It is based on the literature analysis in Chapter 2 and addresses the methodological gaps identified in the reviewed studies. As demonstrated in the initial balance of the "construction and use" field of action [2] emissions are calculated for each sector based on economic transactions and their respective emission intensities. These MRIO models analyse cross-sectoral economic links in Germany's construction and real estate industry. Future approaches should integrate European economic classification systems such as NACE [31], to increase detail and align national with international economic data. This model enables the analysis of the entire supply chain, including upstream and downstream processes such as material extraction, production, and transportation. In contrast, the process-based LCA uses flow diagrams to detail the individual processes of a product's life cycle according to the modules of DIN EN 15978:2012-10. Emissions are calculated separately for each phase. Using the emission factor method, activity data (e.g., material use, transport distances, energy needs) is multiplied by emission factors from databases like Ökobaudat [17]. Based on the structure proposed by BBSR [2]: building materials, construction activities, use and operation, disposal of building materials, and potential for reuse, recovery, and recycling based on [2]. After the quantification of all individual subcategories, the results were combined to enable a holistic assessment of the German construction and building sector for the years 2021, 2022, and 2023. A comprehensive inclusion of all subcategories corresponds to a cradle-to-cradle perspective, while limiting the assessment to Modules A-C results in a cradle-to-grave view. It is also possible to examine specific subcategories individually, for example to focus on particular life cycle phases. This modular structure forms the basis for tiered application levels, as essential for future-proof GHG quantification. It enables the identification of emission hotspots and the derivation of transformation-oriented GHG budgets and benchmarks, while ensuring methodological compatibility between bottom-up and top-down approaches.

3.2.1 Quantification of building materials

The quantification of building materials follows a bottom-up approach, primarily based on the methodology developed by Volk [9] and methodologically extended by Rheude & Röder [19]. The extension includes the additional consideration of import and export data to enable a consumption-based and more realistic GHG inventory that goes beyond conventional territorial boundaries. In contrast to the more limited material scope in Rheude & Röder, which focuses on structural materials, this study, following Volk includes the full spectrum of construction materials. While [9] used approximately 500 datasets, the current database comprises 1,898 datasets assigned to 175 material groups. Material consumption is derived from national production statistics supplemented by import volumes and reduced by exports and multiplied by emission factors from the Ökobaudat for the years 2021 to 2023. The quantification focuses on the life cycle stages A1-A3 (material supply, transport, manufacturing). Optionally, modules C1–C4 (deconstruction, transport, waste processing, disposal) and D (reuse, recovery, and recycling potential) may also be included. Emissions are differentiated between GWP fossil, biogenic, land-use change and forestry-related (LULUCF) [17]. As noted by [19] a differentiation between new and existing buildings, or between residential and non-residential typologies, is currently not feasible using this method. The aim is to provide a realistic estimation of embodied emissions for the entire assessment period. Results can be presented either on a consumption-based or production-based basis, allowing comparability with previous studies such as [9]. Linking material-specific LCA data with statistical consumption data remains challenging due to differing levels of aggregation and detail. While Ökobaudat offers detailed indicators, production and trade statistics use broader categories. This mismatch requires careful dataset selection, and double counting can only be minimized, not entirely avoided.

3.2.2 Quantification of construction activities

The quantification of emissions from construction activities follows a top-down approach, based on BBSR [2], which was originally applied for capturing emissions in the area of use and operation of buildings. The top-down assessment links the final energy consumption of residential and non-residential buildings, infrastructure, and civil engineering works with GWP100 factors from the KBOB [15] life cycle inventory. Based on national statistics, energy consumption is broken down by energy carrier and construction activity type. This allows for the estimation of both direct GHG emissions from on-site energy use and upstream emissions associated with the production of energy carriers. The analysis covers the years 2021 to 2023. Relevant data is derived from the environmental-economic accounting system or other national statistics. For the emission assessment, national GHG factors are used in addition to the KBOB dataset [15] and the BBSR approach [2], in order to reflect country-specific conditions - including electricity and district heating mixes - close data gaps, and enable a transparent, cause-specific monitoring of progress. This logic is applied to the subcategory "construction activities" within the methodology developed here by using the energy consumption of the construction sector - likewise differentiated by energy carriers - as the basis. In the developed methodology, emissions from A1–A3 (material production) are not directly included under construction activities but are integrated into the building materials category. This separation ensures methodological clarity, avoids double counting, and reflects the fact that A1-A3 emissions are more accurately captured through a bottom-up approach based on material-specific data. Due to data limitations, especially regarding import and export structures, a direct allocation of A1-A3 emissions to construction activities would risk significant overestimations. The relevant life cycle phases in the construction activities include A5, which accounts for emissions from on-site construction, B2-B4, which capture emissions from maintenance (B2), repair (B3), replacement (B4) and C1, which quantifies emissions from deconstruction activities. Due to data gaps, emissions from the transportation of materials to construction sites (A4) are not included in the assessment.

3.2.3 Quantification of use and operation

Operational emissions in the use and operation phase are estimated via a top-down approach based on BBSR [2] including direct emissions from building energy consumption and indirect emissions from energy carrier production. Module B6 (electricity and heating demand) is included. Module B7 (water supply) is not considered. However, this aspect could be integrated into future work to enable a more comprehensive environmental assessment. The calculation is based on the annual final energy demand of residential and non-residential buildings, linked to specific emission factors (GWP100) from the KBOB database [15] and supplemented by national data sources. The German electricity and district heating mix for the years 2021 to 2023 is taken into account; where recent data are unavailable, the previous year's composition is used as a proxy. Emission factors per kilowatt-hour are derived from the weighted shares of the energy carriers in the respective mix. Losses from district heating provision are systematically included. The underlying data consist of sector- and end-use-specific energy consumption statistics. For residential buildings, data from the “private households” sector are used; for non-residential buildings, the sectors “commerce, trade, and services (GHD)” and “industry” are included to capture energy use in industrial facilities. The methodological allocation follows BBSR (2020) and covers space heating, hot water, cooling, and lighting; for residential buildings, it also includes process heat, process cooling, mechanical energy, and other relevant end uses. Aggregate statistical categories are, where possible, disaggregated and assigned to individual energy carriers with available emission factors. Renewable energy sources are differentiated according to their typical distribution in national statistics. Total emissions are calculated by multiplying energy consumption by the respective emission factors, followed by sectoral aggregation.

3.2.4 Quantification of material disposal and recycling potential

Material disposal and recycling potential are quantified using a extended bottom-up approach based on Volk [9] and Rheude & Rhöder [19]. The methodological concept involves linking national production and consumption data on building materials with material-specific LCA data. For each material, the corresponding GWP100 values from the Ökobaudat are used for Modules C2 (transport to disposal/recycling), C3 (waste processing for reuse, recycling, and energy recovery), and C4 (final disposal) and multiplied by the respective material quantities. Emission estimates are derived based on the mass of the employed building materials, applying both production-, and consumption-based calculations in a methodologically consistent manner. Aggregation results in an estimate of total emissions arising from the disposal of building materials within the assessment period. Additional assumptions are required for the calculation and must be considered when interpreting the results. In particular, it should be noted that disposal processes concern materials installed decades ago. Since no sufficiently detailed material-specific disposal data are available at the national level for these past periods, the present methodology assumes that currently used materials are representative of those currently being disposed of. The results should therefore be understood as a methodological approximation, which nonetheless plays a central role in the comprehensive accounting of greenhouse gas emissions across the life cycle of construction products.

3.2.5 Potential for reuse, recovery, and recycling

Unlike the existing approaches, such as those by Volk [9], Rheude & Röder [19], BBSR [2], the potential for reuse, recovery, and recycling is assessed separately using a trade-adjusted material flow approach. Module D estimates recycling and material recovery potential, contributing to macroeconomic emissions reduction scenarios. However, it is not a life cycle phase but an additional module quantifying potential recovery effects, which do not imply direct emissions reductions at the building level but support broader circular economy assessments. This module captures potential effects for emissions reduced through the substitution of future production processes by reintegrating secondary materials into the economic cycle. The methodological approach begins by estimating the annual GHG avoidance potential through the combination of material-specific life cycle data and national consumption figures. Corresponding GWP100 values for Module D1 are drawn from the Ökobaudat database [17], which provides standardized substitution potentials for a wide range of common construction materials. Material quantities are multiplied by the respective credits per mass unit to calculate the theoretical emission reduction potential. Since not all materials used in construction are actually recovered or recycled, the theoretical avoidance are subsequently adjusted using a weighting factor. This factor is based on national recovery rates for construction and demolition waste, serving as a proxy for the proportion realistically achieved. The potential savings are multiplied by this rate to derive a more realistic estimate of avoided emissions under Module D. The recovery rate is held constant throughout the observation period and is based on the most recent available national waste statistics. Where no value is available for a given year, the most recent figure is used. This ensures that only the share of substitution potential that is practically realized within the national waste management system is included. The results outline possible emission pathways, informing policy and industry discussions on balancing material consumption, waste generation, and circular strategies. Comparing scenarios with and without Module D1 allows an evaluation of circular economy contributions at national level without affecting core emissions accounting at the building level.

4. Conclusion

This study develops a hybrid framework for GHG quantification in the German construction and real estate industry that combines top-down macroeconomic indicators with bottom-up life cycle data in order to answer the research question. The main contribution lies in the integration of previously disconnected datasets, the differentiation between embodied and operational emissions across all life cycle phases and the alignment with the DIN EN 15978 structure. Without a clearly defined starting point, establishing a sectoral carbon budget and aligning reduction pathways with national and international climate targets remains challenging**.** The proposed framework addresses this issue by systematically linking consumption-based material flows, energy statistics, and emission factors to enable a harmonized, cause-specific accounting of emissions. It offers comprehensive coverage of building materials, construction activities, use and operation, disposal, and the potential for reuse and recycling. By extending existing models such as Volk [9] and Rheude & Röder [19] and BBSR [2], it introduces a disaggregated and consumption-based logic that improves emission attribution and comparability. Beyond the initial balance, continuous quantification of emissions is necessary to monitor the sector's progress toward decarbonization. The framework facilitates the systematic tracking of emissions across all life cycle phases, ensuring that both embodied and operational emissions are considered. This allows for the adaptation of mitigation strategies. International hybrid models by Giesekam et al. [20] and O'Hegarty & Kinnane [21] illustrate how MRIO models and scenario-based allocation logic can enhance transparency and transferability, especially for full life cycle coverage and sectoral integration. Although these dynamic models are discussed in Chapter 2, their systematic integration into hybrid emissions accounting frameworks remains a key research gap. Future work should further explore their potential to support scenario-based assessments and transformation-aligned carbon budgeting.

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