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# Greenhouse Gas Accounting for Germany's Building, Construction and Real Estate Sector: Linking Life-Cycle Modules and Annual Activities

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# Greenhouse Gas Accounting for Germany's Building, Construction and Real Estate Sector: Linking Life-Cycle Modules and Annual Activities

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**Abstract**

The building, construction and real estate (BCRE) sector is a major contributor of Germany's greenhouse gas (GHG) emissions. However, existing accounting approaches remain inconsistent due to differing system boundaries and allocation principles. This study develops a reproducible, automated hybrid approach to quantify annual GHG emissions arising from activities, using 2022 as the reference year. Annual embodied GHG emissions are quantified by combining bottom-up material-flow data on production, trade, and waste with material-specific life-cycle assessment (LCA) emission factors. End-of-life treatment is explicitly modeled by classifying waste flows as mono-material, composite, or multi-component products and assigning them to recycling, energy recovery, landfill, or other disposal routes, including potential benefits beyond the product system. In contrast, annual operational emissions are calculated using an energy-based top-down approach, in which final energy consumption in residential and non-residential buildings is combined with energy carrier specific GHG emission factors.

In 2022, Germany's BCRE sector caused 362.9 Mt $CO_2$e from domestic consumption, equivalent to 40.3% of the national total of 901.3 Mt $CO_2$e. Total GHG emissions are distributed across economic activities, with 23.3% attributable to the manufacturing of construction products, 2.7% to construction and deconstruction activities, 72.1% to energy-related GHG emissions caused by the use and operation of residential and non-residential buildings, and 1.9% to end-of-life treatment. Potential benefits from waste treatment are reported separately

and are not included in these gross sectoral emissions, but may reduce the embodied-emission share in the net assessment when these credits are taken into account. They amount to about 3.2% of the gross footprint and are mainly driven by recycling-related credits, while landfill and energy recovery make smaller contributions.

**Keywords:** carbon footprint, annual activities, embodied emissions, automated framework

# 1 Introduction

Given ambitious climate targets, including the 1.5°C goal (UN 2015), which is increasingly considered out of reach, and growing pressure on planetary boundaries (Rockström et al. 2009), the BCRE[1] sector plays a key role in climate change mitigation. At the national level, mitigation efforts under the Paris Agreement are framed through nationally determined contributions (NDCs) (UN 2015). In this context, carbon footprint[2] accounting is gaining importance as it determines how the sector's emissions are assessed in relation to remaining carbon budgets[3] and how mitigation pathways are defined. The built environment accounts for 37% of global $CO_2$ emissions (UNEP and GlobalABC 2026) and around 47% of total anthropogenic emissions in the EU (EEA 2024).

Germany, as the EU's largest economy and construction market, represents a particularly relevant case, although estimates of the sector's contribution vary widely. Official statistics report shares of about 20%, as they primarily capture direct operational emissions from fuel combustion in residential and non-residential buildings (UBA 2024). By contrast, broader assessments indicate shares of up to 37% (UNEP and GlobalABC 2026). These assessments can be structured according to the modular logic of DIN EN 15978:2026-09[4], while adapting it to annual sectoral activities.

These differences reflect divergent accounting principles and system boundaries. Emissions associated with the BCRE sector arise across economic sectors and national borders. As a result existing approaches account for sectoral interrelations and trade-related flows differently, resulting in fragmented emission estimates that are difficult

[1] In this study, the term *Building, Construction and Real Estate (BCRE) sector* refers to the German *Bau- und Gebäudebereich* and includes activities, supply chains, processes and stakeholders across the whole life cycle of buildings and infrastructure (UNEP 2023).

[2] For the purpose of this paper, "carbon footprint" denotes annual GHG emissions, expressed as $CO_2e$, associated with activities in Germany's BCRE sector in the reporting year. This use follows the understanding of carbon footprinting as emissions directly and indirectly caused by an activity (Wiedmann and Minx 2008). It does not refer to a building-level life cycle assessment (LCA) or to an Environmental Product Declaration (EPD) under (IPCC 2018).

[3] Carbon budgets refer to cumulative $CO_2$ emissions that are compatible with a given temperature limit and depend on assumptions regarding non-$CO_2$ forcing and climate response (IPCC 2018), thereby translating the climate-change boundary within the planetary boundaries framework into a quantifiable emissions constraint (Rockström et al. 2009).

[4] DIN EN 15978:2026-09 structures building-related environmental impacts into the product stage (A1–A3, raw material supply, transport, and manufacturing), the construction process stage (A4–A5, transport to the building site and construction and installation processes), the use stage (B1–B7, use, maintenance, repair, replacement, refurbishment, operational energy use, and operational water use), the end-of-life stage (C1–C4, deconstruction, transport, waste processing, and disposal), and Module D, which covers potential benefits and loads beyond the system boundary from reuse, recovery, and recycling (DIN 2026).

to compare from the material, component, and building level to sectoral and national statistics (Kaya et al. 2026).

In response to these methodological challenges, this study develops an automated accounting framework that links annual economic activities in Germany's BCRE sector with LCA-based emission factors and national statistical reporting. By combining product-level material flows with sectoral activity data, the framework assigns operational, upstream energy-related, and embodied emissions to a consistent reporting structure. This improves the transparency and comparability of annual GHG emission estimates for Germany's BCRE sector and provides a basis for standardized monitoring and benchmarking at building stock level. Against this background, the study is guided by the following research question:

*How can the carbon footprint of Germany's BCRE sector be consistently quantified and integrated into national statistics?*

To address this research question, the study is structured as follows. Section 2 reviews existing approaches to sectoral and life-cycle-based GHG accounting. Section 3 presents the methodological framework and data integration. Section 4 applies the framework to the German BCRE sector and discusses the resulting carbon footprint. Finally, Section 5 discusses the limitations of the assessment, while Section 6 concludes the study and derives recommendations for standardized cross-sectoral GHG accounting of the BCRE sector at the national level.

## 2 State of the Art

The carbon footprint of Germany's BCRE sector is only partially visible in official statistics. Figure 1 therefore aligns four interrelated classification frameworks used in German research, standards, and reporting. Rather than following a single reading direction, the framework converges on Column II, which provides the common annual activity-based reference for linking product- and building-level life-cycle information in Columns III and IV with emissions distributed across sectors of the German Federal Climate Change Act (KSG) in Column I and attributing them to the BCRE activities whose demand induces them.

Column IV represents the product-level modules of DIN EN 15804:2022-03 used in Environmental Product Declarations (EPDs) (DIN 2022). EPDs provide detailed emission factors but no annual national product quantities. Column III embeds these processes within the building-level life-cycle modules of DIN EN 15978:2026-09 (DIN 2026). In EU Member States, including Germany, building LCAs typically apply a 50-year reference study period and are institutionalized through the Assessment System for Sustainable Building (BNB) and the Quality Seal for Sustainable Buildings (QNG), where they support standardized benchmarking and, in the case of QNG, funding eligibility (BMWSB 2008, 2021, 2023). Their building-specific functional units and multi-year assessment periods nevertheless prevent direct transfer to annual national accounting.

Column II provides the annual activity-based link between national economic accounting and life-cycle assessment. Building on the field of action "construction and operation of buildings," top-down approaches combine Environmental-Economic

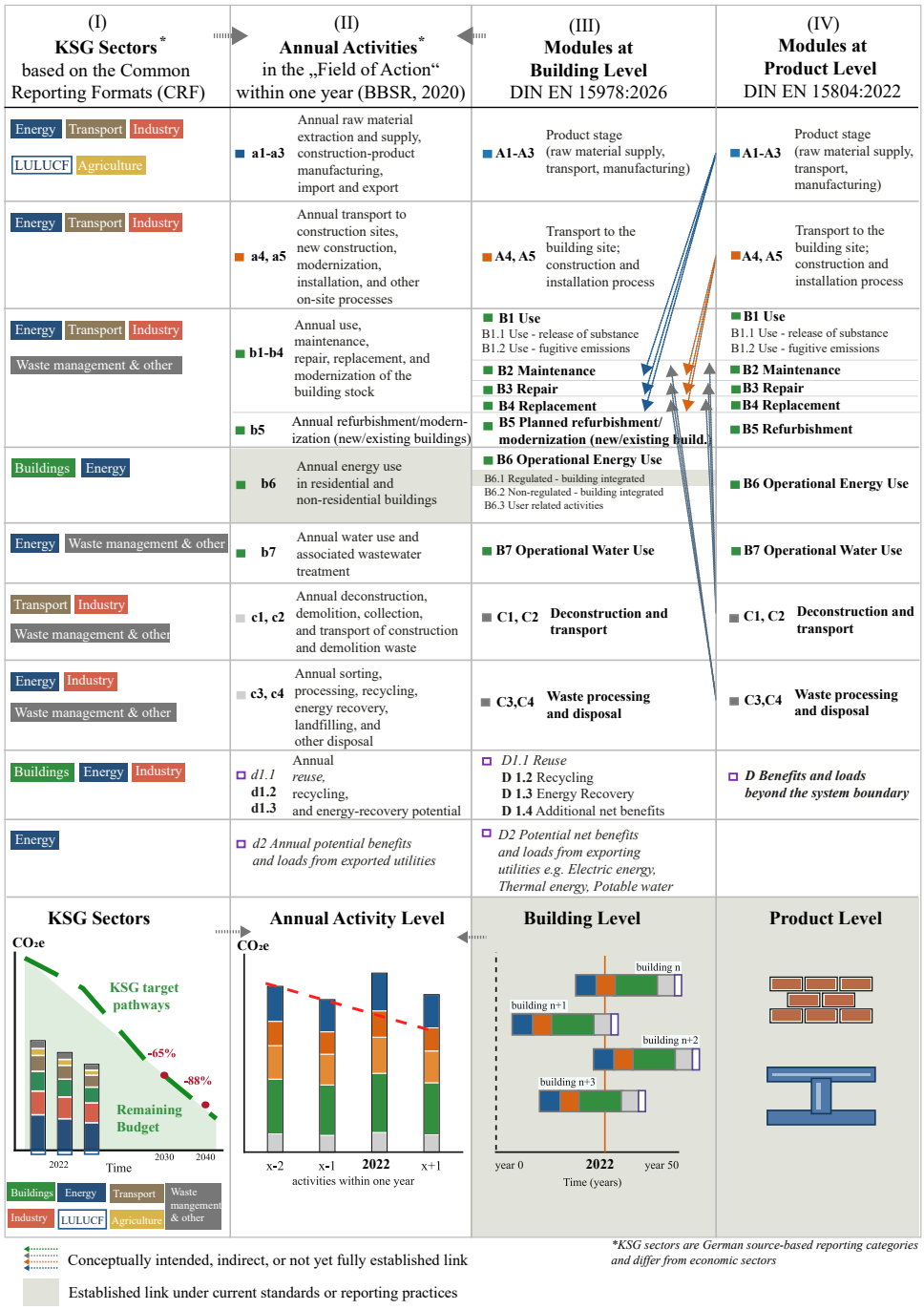



**Fig. 1** Alignment of KSG source sectors, annual BCRE activities, and building- and product-level life-cycle modules. Columns III and IV link life-cycle modules to annual activities, while Column I shows where domestic emissions are reported. Upright elements are quantified, whereas italicized elements are excluded or not assessed separately. Adapted and further developed from Lützkendorf (2020).

Accounts (EEA) with environmentally extended multi-regional input-output (MRIO) analysis to attribute domestic and imported supply-chain emissions to the final demand for construction and building use (BBSR 2020; Destatis 2025c; Stadler et al. 2018). This establishes a common reporting-year perspective across activities that are otherwise distributed among several economic sectors. However, the aggregated representation of products and technologies limits material- and process-level detail.

Bottom-up material flow analysis (MFA) approaches complement this perspective by linking product-level environmental data in Column IV to annual BCRE activities in Column II through production and trade statistics and EPD-based emission factors from the German national ÖKOBAUDAT database (Rheude and Röder 2022; Volk 2024; BMWSB 2024). Existing studies demonstrate this connection for selected construction-product flows, but cover only parts of the building life cycle. They therefore provide the product detail missing from top-down accounting without yet forming an integrated national framework that includes operational energy use, end-of-life treatment, and Module D as additional information on benefits and loads beyond the system boundary according to DIN EN 15978:2026-09.

Column I anchors the demand- and life-cycle-based perspectives in official source-based reporting under the KSG and its Common Reporting Format (CRF) categories (BMUV 2014). Rather than defining the BCRE sector, these categories indicate where domestic emissions are released and reported. The Buildings sector mainly captures direct on-site combustion as part of B6.1 under DIN EN 15978:2026-09, while electricity and heat generation, product manufacturing, transport, and waste treatment are assigned to Energy, Industry, Transport, and Waste management and other. Emissions generated outside Germany and embodied in imports remain outside the territorial inventory, while the EEA distribute domestic emissions across resident economic activities and private households. Neither system therefore provides a distinct BCRE-sector total.

The connections integrate fragmented emissions within a common annual life-cycle framework while retaining their formal KSG attribution. For instance, A1–A3 factors from Column IV are assigned to the building product stage in Column III and linked to annual production and trade flows in Column II. Column I then distinguishes domestic emissions reported mainly under Industry and Energy from imported emissions included only in the demand-based footprint. This preserves both their life-cycle origin and official reporting location, a linkage not yet applied consistently across all annual activities.

# 3 Methodological Framework and Data Integration

The methodological framework in Figure 2 operationalizes the activity-based bridge established in Figure 1. It quantifies parallel annual activities of the BCRE sector for the 2022 reporting year and links them to the corresponding life-cycle modules where suitable GHG emission factors are available. Rather than assessing individual building life cycles, the module structure provides a common framework for annual accounting of the BCRE sector. Results are reported as GWP-total in carbon dioxide equivalents ($CO_2e$) (IPCC 2018). The framework is automated because input

data, mappings, emission factors, calculations, and results are connected through a reproducible workflow that can be updated for subsequent reporting years.

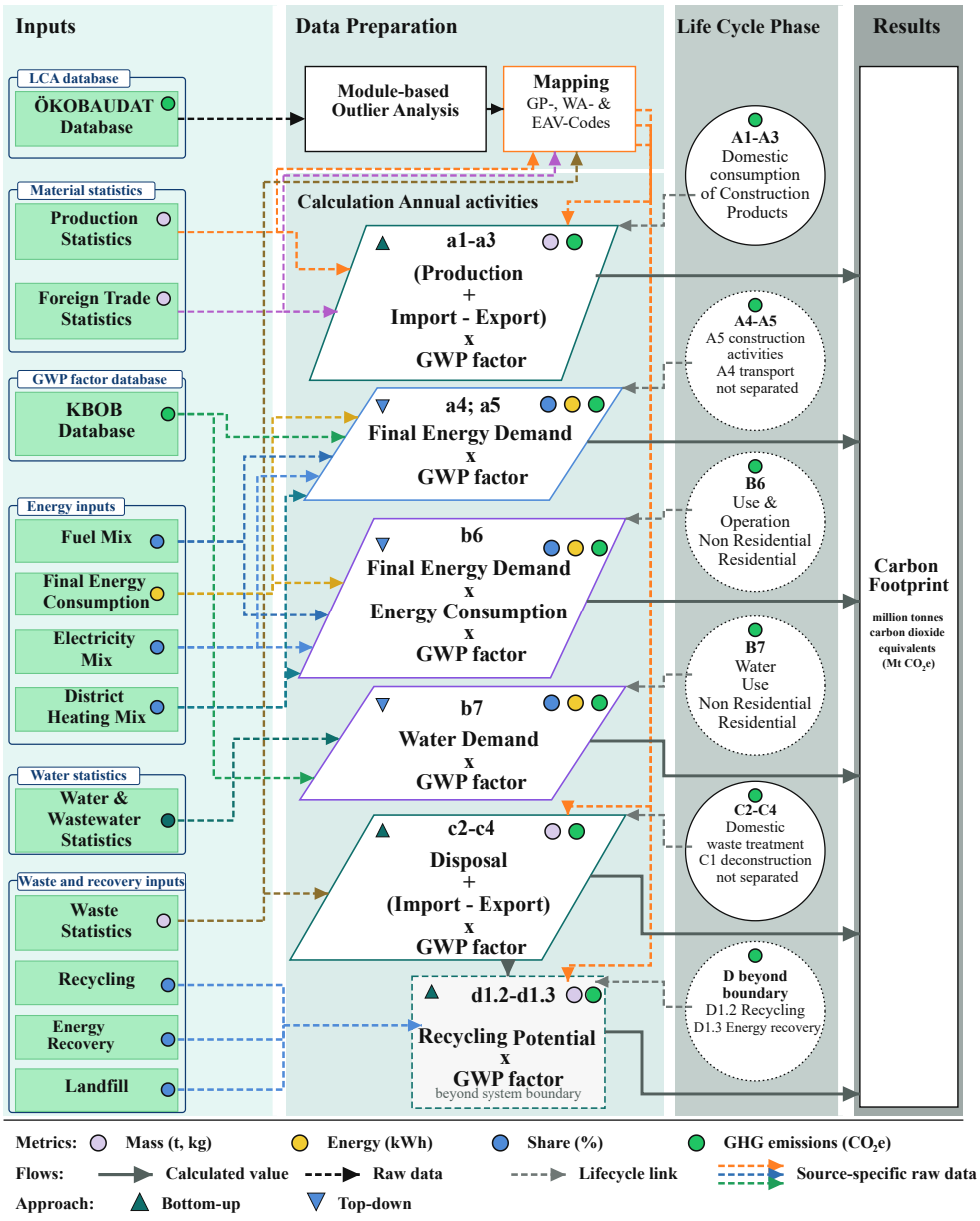



**Fig. 2** Automated framework for assessing GHG emissions of the BCRE sector

The bottom-up component quantifies material-related annual BCRE activities, comprising domestic construction-product consumption (a1–a3), end-of-life treatment (c2–c4), and potential recycling and energy-recovery effects beyond the system boundary (d1.2–d1.3). Production, trade, and waste statistics are linked to product- and treatment-specific EPD-based GHG emission factors from ÖKOBAUDAT. Before calculation, the underlying datasets are screened for outliers and unit plausibility and mapped across production, trade, and EAV waste classifications.

Potential effects from recycling and energy recovery are calculated using Module D1 factors and reported separately from the gross annual BCRE footprint because they represent possible substitution effects beyond the system boundary. These effects may occur in other sectors, countries, or reporting years and are therefore not assigned to current BCRE or KSG emissions. Reuse (d1.1) and exported utilities (d2) are excluded because the available statistics do not provide sufficient activity data. Effects associated with the use of secondary materials may already be reflected in the published A1–A3 factors and are not recalculated.

The top-down component quantifies construction and deconstruction activities (a4–a5), operational energy use (b6), and operational water use (b7) by linking sectoral energy, water, and wastewater flows to carrier- or process-specific GHG emission factors. Transport to construction sites and deconstruction activities are included within the conceptual boundary but cannot be separated consistently from aggregated construction-sector and waste data because activity-specific energy use and transport distances are unavailable. Domestic hot-water energy remains assigned to b6 to avoid double counting.

Activities b1–b5 are not quantified separately because the available data do not identify maintenance, repair, replacement, and refurbishment by component, service life, or replacement cycle. However, the manufacture of products used for these activities may be included in a1–a3 where it is captured by annual production and trade statistics. Detailed data sources, screening procedures, mappings, and calculations are documented in the respective subsections and Supplementary Information. The resulting activity-level emissions are aggregated to determine the 2022 carbon footprint of Germany's BCRE sector.

## 3.1 Quantification of Construction-Product Manufacturing Emissions (a1–a3)

Annual activity a1–a3 quantifies construction-product emissions from production- and consumption-based perspectives, following previous German assessments (BBSR 2020). The production-based perspective covers products manufactured in Germany, while the consumption-based perspective adds imports and subtracts exports to approximate products used within Germany. Construction products comprise finished and semi-finished products reported in production and trade statistics and linked to ÖKOBAUDAT, including selected permanently installed building-service products.[5] Because the statistics do not report final applications, emissions cannot be allocated to buildings or infrastructure, or to new construction, modernization, replacement,

[5]Primary raw materials and precursor datasets are excluded to avoid double counting.

and other uses. Emissions for the 2022 reporting year are calculated according to Equation 1.

$$\mathrm{GHG}_{a1-a3,y} = \sum_{i \in I} \left(\mathrm{Production}_{i,y} + \mathrm{Import}_{i,y} - \mathrm{Export}_{i,y}\right) \cdot CF_i \cdot \mathrm{GWP}_{i,a1-a3} \quad (1)$$

where:

- $\mathrm{GHG}_{a1-a3,y}$: Total a1–a3 emissions in reporting year $y$, in kg $CO_2$e.
- $i$: Construction product category.
- $\mathrm{Production}_{i,y}$, $\mathrm{Import}_{i,y}$, $\mathrm{Export}_{i,y}$: Domestic production, import, and export quantities of product $i$ in year $y$.
- $CF_i$: Conversion factor from statistical quantity to ÖKOBAUDAT declared unit.
- $\mathrm{GWP}_{i,A1-A3}$: A1–A3 emission factor in kg $CO_2$e per declared unit.

After calculating apparent domestic consumption, production and trade quantities are converted to the declared units of the mapped ÖKOBAUDAT datasets using product-specific reference masses and conversion factors, ensuring consistency between activity data and emission factors. GP2019 production and WA2021 trade codes are linked through the official concordance to align product coverage across both statistical systems. Where multiple retained ÖKOBAUDAT datasets match one statistical code, the quantity is distributed across the matches to avoid multiple counting. Results are aggregated by harmonized ÖKOBAUDAT top-level category to enable comparison across product and material groups. Data, conversions, concordance, and mapping are documented in Supplementary Information S2.2–S2.5 and S3.4.

## 3.2 Quantification of Construction and Deconstruction Emissions (a4, a5)

Construction and deconstruction processes (a4–a5) are estimated from final energy demand reported for NACE Rev. 2 Section F (Construction), the closest official economic category covering construction, renovation, site preparation, installation, finishing, and deconstruction (EC 2008; Destatis 2008). Because the EEA report this activity only in aggregate, individual sites, machines, transport distances, and processes cannot be distinguished (Destatis 2023). Construction-related fuels, mobile machinery, and temporary site electricity are therefore linked to carrier-specific GHG emission factors (KBOB et al. 2024; BMWSB 2024). The calculation is given in Equation 2, with further details in Supplementary Information S2.6.

$$\mathrm{GHG}_{a4-a5,y} = \mathrm{FED}_{el,y} \cdot \sum_{j \in J_{el}} s_{j,y} \cdot \mathrm{EF}_j + \sum_{m \in J_{fuel}} \mathrm{FED}_{m,y} \cdot \mathrm{EF}_m \quad (2)$$

where:

- $\mathrm{GHG}_{a4-a5,y}$: Total construction and deconstruction emissions in reporting year $y$, in kg $CO_2$e.
- $\mathrm{FED}_{el,y}$: Final electricity demand of the construction sector in reporting year $y$, in kWh.

- $s_{j,y}$: Share of electricity source $j$ in the electricity mix in reporting year $y$.
- $\mathrm{EF}_j$: GHG emission factor of electricity source $j$, in kg $CO_2$e/kWh.
- $\mathrm{FED}_{m,y}$: Final energy demand of fuel or energy carrier $m$ in reporting year $y$, in kWh.
- $\mathrm{EF}_m$: GHG emission factor of fuel or energy carrier $m$, in kg $CO_2$e/kWh.

The first term captures electricity-related emissions using the 2022 German gross electricity generation mix, calculated as the sum of source-specific GHG emission factors weighted by the shares of the individual electricity sources, with renewable sources accounting for 43.1% of the mix (Destatis 2024). The second term captures fuel-related emissions from reported construction sector final energy carriers; within the non-electric fuel demand, fossil fuels account for 94.5% and renewable fuels, represented by biodiesel and bioethanol, account for 5.5% (Destatis 2023). Together, both terms quantify aggregated construction-sector energy emissions assigned jointly to a4–a5. Because the statistics lack transport-distance-, product-, process-, and deconstruction-specific data, a4, a5, and c1 cannot be reported separately, although c1 may be partly included in Section F energy use.

## 3.3 Quantification of Building Use and Operation Emissions (b6, b7)

Use- and operation-related emissions comprise operational energy use (b6) and operational water use (b7). For b6, final energy demand from private households, industry, and commerce, trade, and services (GHD, German: *Gewerbe, Handel, Dienstleistungen*) is filtered by end-use application to retain building-related demand and assign it to residential and non-residential buildings (AGEB 2023; AG Energiebilanzen e.V 2024). Each energy carrier is then linked to a corresponding GHG emission factor (BMWSB 2024; KBOB et al. 2024; UBA 2023). Electricity and district heating are calculated from weighted 2022 German supply mixes, with district heating additionally adjusted for distribution losses.

The b6 scope combines regulated building-integrated (b6.1), non-regulated building-integrated (b6.2), and user- or activity-related uses (b6.3), as the AGEB balances do not consistently separate building services, user demand, and process energy (AGEB 2023; AG Energiebilanzen e.V 2024). Operational energy emissions are calculated according to Equation 3, with the underlying data documented in Supplementary Information S2.7.

$$\mathrm{GHG}_{b6,y} = \sum_{c \in C} (\mathrm{FED}_{res,c,y} + \mathrm{FED}_{nonres,c,y}) \cdot \mathrm{EF}_{c,y} \tag{3}$$

where:

- $\mathrm{GHG}_{b6,y}$: Operational energy emissions in reporting year $y$, in kg $CO_2$e.
- $\mathrm{FED}_{res,c,y}$: Final energy demand of residential buildings for energy carrier $c$ in year $y$.
- $\mathrm{FED}_{nonres,c,y}$: Final energy demand of non-residential buildings for energy carrier $c$ in year $y$.
- $\mathrm{EF}_{c,y}$: GHG emission factor of energy carrier $c$ in year $y$.

b7 is calculated separately from b6 and covers drinking-water supply as well as wastewater collection and treatment. Water and wastewater quantities are taken from official water statistics and differentiated between residential and non-residential buildings. They are combined with process specific electricity intensities and electricity GHG emission factors (Destatis 2022a,d,c; UBA 2000; Fraunhofer 2022) (Supplementary Information S2.8). The emissions of b7 are calculated according to Equation 4.

$$\mathrm{GHG}_{b7,y} = Q_y^{water} \cdot EI_y^{water} \cdot \mathrm{EF}_y^{el} + Q_y^{wastewater} \cdot EI_y^{wastewater} \cdot \mathrm{EF}_y^{el} \tag{4}$$

where:

- $\mathrm{GHG}_{b7,y}$: Emissions from operational water use in reporting year $y$, in kg $CO_2$e.
- $Q_y^{water}$: Drinking-water volume assigned to buildings in reporting year $y$, in $m^3$.
- $Q_y^{wastewater}$: Wastewater volume assigned to buildings in reporting year $y$, in $m^3$.
- $EI_y^{water}$: Electricity intensity of drinking-water supply in reporting year $y$, in kWh/$m^3$.
- $EI_y^{wastewater}$: Electricity intensity of wastewater collection and treatment in reporting year $y$, in kWh/$m^3$.
- $\mathrm{EF}_y^{el}$: Electricity emission factor in reporting year $y$, in kg $CO_2$e/kWh.

Energy demand for heating domestic hot water is assigned to B6 rather than B7 to avoid double counting between operational energy and operational water use.

## 3.4 Quantification of Construction-Product End-of-Life Emissions (c2–c4)

End-of-life activities c2–c4 are quantified by linking consumption-based construction and demolition waste (CDW) flows to route-specific ÖKOBAUDAT GHG emission factors. For each product-specific material fraction $j$, domestic waste generation plus imports minus exports is converted to the declared unit of the mapped dataset using the reference mass $RM_j$. The resulting quantity is allocated to recycling, energy recovery, landfill, and other disposal according to the domestic treatment-route shares of the corresponding EAV category and multiplied by the respective C2–C4 factor (Destatis 2026, 2022b; UBA 2022b,a; BMWSB 2024). Because route-specific data are unavailable for imported and exported waste, the domestic EAV distribution is applied to the complete consumption-based waste balance. Reuse is excluded because it is not reported separately in national waste statistics. Emissions are calculated according to Equation 5

$$\mathrm{GHG}_{c2-c4,y} = \sum_{j \in J} \sum_{r \in R} \left( \frac{\mathrm{Waste}_{j,y}^{dom} + \mathrm{Waste}_{j,y}^{imp} - \mathrm{Waste}_{j,y}^{exp}}{RM_j} \cdot s_{j,r,y} \cdot \mathrm{GWP}_{j,r,c2-c4} \right) \tag{5}$$

where:

- $\mathrm{GHG}_{c2-c4,y}$: Total C2–C4 emissions in reporting year $y$, in kg $CO_2$e.
- $j$: Product specific material fraction assigned to an EAV waste category.
- $r$: Treatment route, including recycling, energy recovery, landfill, and other disposal.
- $\mathrm{Waste}_{j,y}^{dom}$, $\mathrm{Waste}_{j,y}^{imp}$, and $\mathrm{Waste}_{j,y}^{exp}$: Domestic waste generation, waste imports, and waste exports of $j$, converted to kg.
- $RM_j$: Reference mass per declared unit, in kg.
- $s_{j,r,y}$: Domestic treatment-route share.
- $\mathrm{GWP}_{j,r,C2-C4}$: Route specific C2–C4 factor from ÖKOBAUDAT, in kg $CO_2$e per declared unit.

The treatment-route share $s_{j,r,y}$ is calculated from the domestic treatment-route distribution of the corresponding EAV waste category according to Equation 6.

$$s_{j,r,y} = \frac{\mathrm{Waste}_{j,r,y}^{dom}}{\mathrm{Waste}_{j,y}^{dom}} \tag{6}$$

where:

- $\mathrm{Waste}_{j,r,y}^{dom}$: Domestic waste mass of product specific material fraction $j$ assigned to treatment route $r$ in reporting year $y$, in kg.
- $\mathrm{Waste}_{j,y}^{dom}$: Total domestic waste mass of product specific material fraction $j$ in reporting year $y$, in kg.

Hazardous CDW is excluded and reported separately because pollutant-specific treatment requirements prevent consistent linkage to the generic material-specific C2–C4 and Module D1 factors used here (Supplementary Information S2.10 and S3.11). For non-hazardous CDW, mono-material products are assigned directly to material-specific EAV categories, whereas composite and multi-component products are decomposed into material fractions using ÖKOBAUDAT product information and the documented composition mapping. This ensures consistency between product flows, EAV waste quantities, treatment routes, and GHG emission factors (Supplementary Information S3.4 and S3.6).

Route-specific C2–C4 factors are available for only 26 of 540 recycling datasets, 30 energy-recovery datasets, and 19 landfill datasets. Each waste quantity is therefore first distributed across recycling, energy recovery, landfill, and other disposal using $s_{j,r,y}$ and then multiplied by the corresponding factor $\mathrm{GWP}_{j,r,C2-C4}$. Where no route-specific factor is available, standard-scenario or generic C2–C4 values are applied according to the fallback hierarchy in Supplementary Information S3.11.

## 3.5 Quantification of Potential Beyond-System Effects (d1.2–d1.3)

Annual activities d1.2–d1.3 are reported separately because they represent potential benefits and loads beyond the system boundary. They are therefore not deducted from the gross annual footprint comprising a1–a3, a4–a5, b6, b7, and c2–c4. The calculation uses the route-specific waste masses derived for c2–c4 in Section 3.4 and links them to the corresponding Module D1 factors from ÖKOBAUDAT (BMWSB 2024).

The calculation of d1.2–d1.3 is expressed in Equation 7.

$$\mathrm{GHG}_{d,y} = \sum_{j \in J} \sum_{r \in R} \frac{\mathrm{Waste}^{cons}_{j,r,y} \cdot 1000}{RM_j} \cdot \mathrm{GWP}_{j,r,D} \tag{7}$$

where:

- $\mathrm{GHG}_{d,y}$: Potential benefits d1 or loads in reporting year $y$, in kg $CO_2$e.
- $j$: Product specific material fraction assigned to an EAV waste category.
- $r$: Treatment route as defined in Section 3.4, including recycling, energy recovery, landfill, and other disposal.
- $\mathrm{Waste}^{cons}_{j,r,y}$: Consumption-based waste mass of product specific material fraction $j$ assigned to treatment route $r$ in reporting year $y$, in tonnes. The factor 1000 converts tonnes to kg.
- $RM_j$: Reference mass per declared unit, in kg.
- $\mathrm{GWP}_{j,r,D}$: Route specific Module D1 factor from ÖKOBAUDAT, in kg $CO_2$e per declared unit.

Negative values indicate potential GHG reductions beyond the system boundary and occur for 439 of the 540 mapped ÖKOBAUDAT datasets after linkage to EAV-based waste flows. Because these effects may arise in downstream production systems, later reporting years, or outside Germany, for example through the substitution of primary materials, they are reported separately rather than deducted from the annual footprint. Credits and burden shifts already embedded in the EPD-based factors are retained as dataset-specific assumptions and are not recalculated or reallocated, which would introduce additional uncertainty.[6]

Route-specific Module D1 factors are used where available. Missing factors are replaced first by product-specific standard-scenario values and then by generic Module D1 values according to the fallback hierarchy in Supplementary Information S3.12. Reuse activity d1.1 is not quantified because national waste statistics do not report it as a separate treatment route.

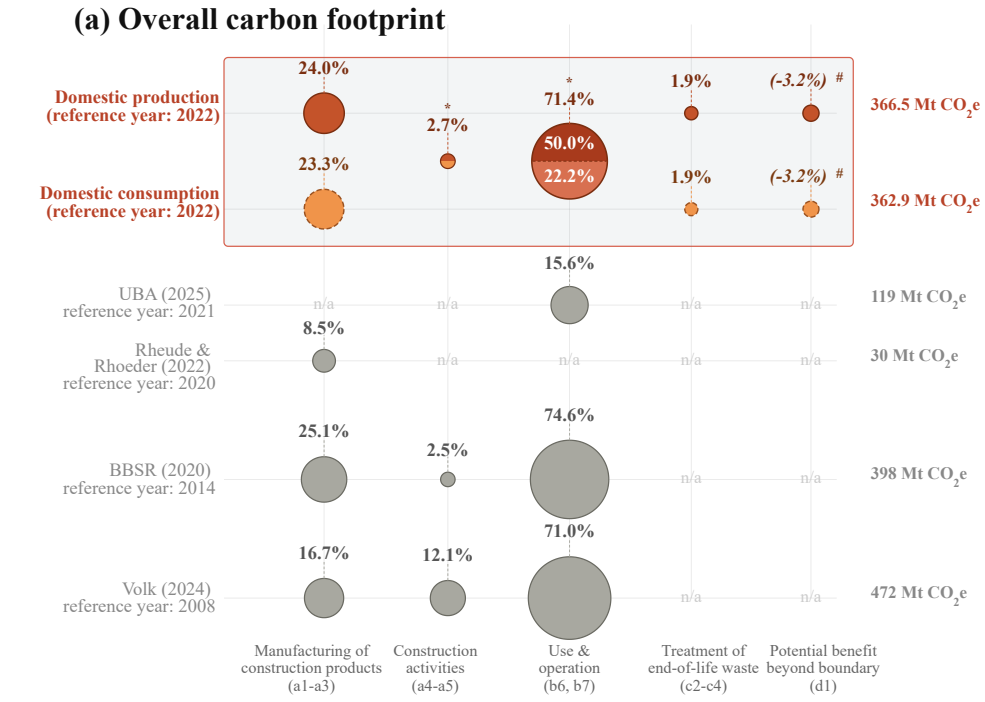
# 4 Results and Discussion

## 4.1 Overall Carbon Footprint and Comparison with Previous Studies

The domestic-consumption carbon footprint of Germany's BCRE sector amounted to 362.9 Mt $CO_2$e in 2022, equivalent to 40.3% of the national resident-principle total of 901.3 Mt $CO_2$e (Destatis 2025c). The domestic-production perspective yields a slightly higher footprint of 366.5 Mt $CO_2$e. Potential benefits from recycling and energy recovery beyond the system boundary are reported separately in both perspectives.

Figure 3 distinguishes differences in life-cycle coverage from differences in total magnitude. Panel (a) compares the activity-level composition of the model results with the scopes of previous studies, while panel (b) relates the estimates to national GHG trends and earlier sectoral assessments.

[6] For example, cement EPDs may allocate impacts from co-incinerated plastic or biogenic waste-derived fuels between cement production, the waste-generating system, and the substituted fuel. Consequently, not all emissions physically released during production are necessarily attributed to the cement product.



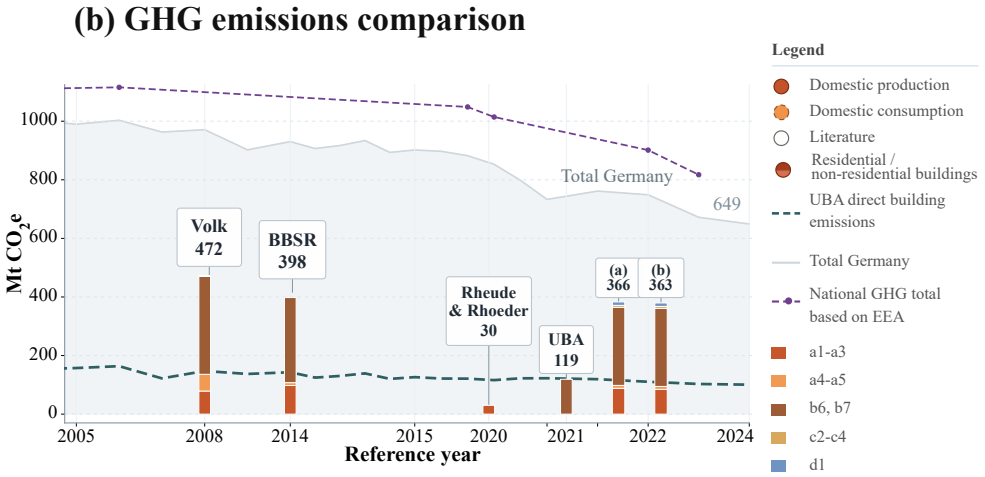




**Fig. 3** Carbon footprint comparison of the German BCRE sector with previous estimates. Panel (a) compares the activity-level composition of the model results with literature values and scope specific reference points, while panel (b) places the estimates in relation to national GHG emission trends and previous sectoral assessments.

Under the domestic-consumption perspective, use and operation (b6 and b7) dominate the gross footprint with 72.1%. Construction-product sourcing and manufacturing (a1–a3) contribute 23.3%, construction and deconstruction processes (a4–a5) 2.7%, and end-of-life treatment (c2–c4) 1.9%. The domestic-production perspective shows a similar distribution, with shares of 71.4%, 24.0%, 2.7%, and 1.9%, respectively. The higher a1–a3 share reflects the 2022 trade balance, in which construction-product exports exceeded imports. Potential effects from recycling and energy recovery (d1.2–d1.3) amount to −11.7 Mt $CO_2$e, equivalent to 3.2% of the gross footprint, but are not deducted because they occur beyond the assessed system boundary.

Percentage values in panel (a) are directly comparable only for studies with similarly broad life-cycle coverage. For narrower estimates, they refer to more limited system boundaries rather than to a common whole-life-cycle BCRE footprint. The 119 Mt $CO_2$e reported for direct building-related emissions in 2021 mainly cover on-site fossil-fuel combustion (UBA 2025). They exclude electricity and district-heating generation, upstream energy supply, construction-product manufacturing, construction processes, and end-of-life treatment, which are included in the present assessment. The approximately 30 Mt $CO_2$e reported for shell construction materials (Rheude and Röder 2022) likewise represent a narrower material scope. Both values are therefore included as scope-specific reference points rather than complete BCRE-sector footprints.

Despite these differences, the modeled composition is close to the 75% operational and 25% upstream distribution reported by BBSR (2020). The total magnitude is also comparable to broader estimates of 398 Mt $CO_2$e (BBSR 2020) and 442–472 Mt $CO_2$e (Volk 2024). Remaining differences mainly reflect reference years, system boundaries, product coverage, and the omission of c2–c4 and d1 from previous assessments.

## 4.2 Annual GHG Emissions from Construction-Product Manufacturing and End-of-Life Activities

In 2022, domestic construction-product consumption amounted to 211.7 Mt, comprising 228.1 Mt of domestic production, 66.9 Mt of imports, and 83.2 Mt of exports. Since trade statistics do not identify whether exported goods were produced domestically or previously imported, exports are allocated proportionally to both sources. The underlying calculations are documented in Supplementary Information, Section S2.

As shown in Figure 4(a), the consumption estimate lies between previous German estimates of 119 Mt from a bottom-up stock assessment excluding civil engineering (Schiller et al. 2015) and approximately 242 Mt from a broader top-down assessment including raw materials (Schiller et al. 2017).

This intermediate value reflects the broad product coverage of the present framework and the exclusion of primary raw materials to avoid double counting. Based on the proportional export allocation, 71.8% of domestically produced construction products remain in Germany, corresponding to 163.7 Mt. The higher retention share of 92.7% and lower inflows of approximately 126–140 Mt reported by Rheude and Röder (2022) result mainly from their narrower focus on shell construction materials and the exclusion of civil engineering, raw-material extraction, and deconstruction.

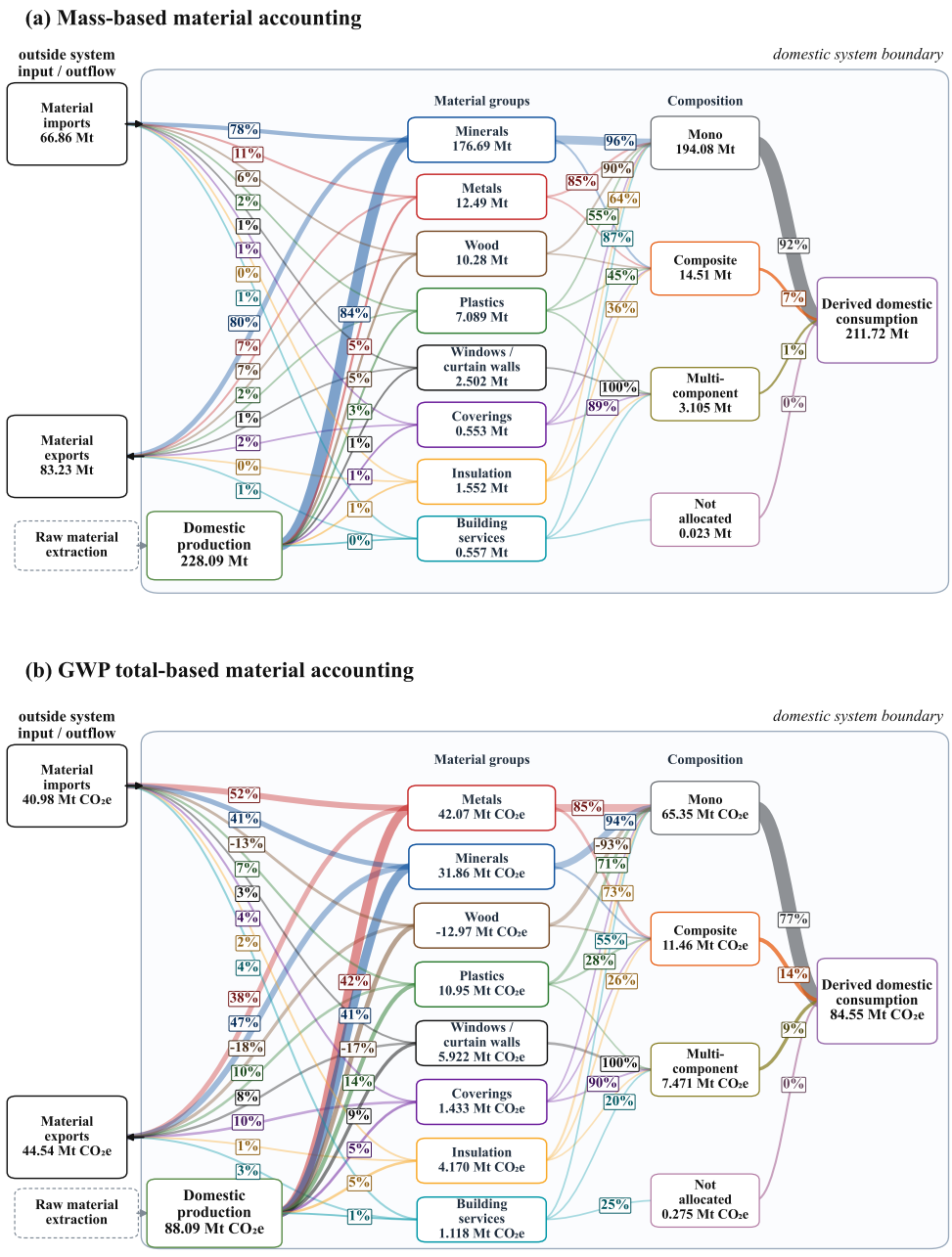



**Fig. 4** Material-flow and GWP total accounting of construction products in 2022. Panel (a) shows the mass-based material accounting, while panel (b) shows the corresponding GWP total-based accounting.

Mineral products dominate domestic consumption with 176.69 Mt or 83.5%, followed by metals with 12.49 Mt, wood with 10.28 Mt, and plastics with 7.09 Mt. Minerals also dominate domestic production, imports, and exports, accounting for approximately 84%, 78%, and 80% of the respective mass flows.

Single-material products account for 194.08 Mt or 91.7% of domestic consumption. Composite and multi-component products contribute 14.51 Mt or 6.9% and 3.11 Mt or 1.5%, respectively, while only 0.02 Mt remain unallocated. This distinction supports the end-of-life allocation, as single-material products can be linked directly to material-specific EAV categories, whereas composite and multi-component products require decomposition into material fractions.

Figure 4(b) shows a marked divergence between mass and climate impact. Metals cause the highest positive contribution at 42.07 Mt $CO_2$e despite their substantially lower mass, while mineral products contribute 31.86 Mt $CO_2$e. Wood products contribute $-12.97$ Mt $CO_2$e because the underlying ÖKOBAUDAT datasets account for biogenic carbon storage. The comparison demonstrates that material mass alone does not determine climate impact and that emission-intensive products can dominate GWP despite comparatively small material flows. At product-family level, the top 24 families account for approximately 88% of A1–A3 consumption, whereas 33 families are required to reach approximately 85% of total net GWP, indicating a more dispersed carbon hotspot structure than the mass distribution.

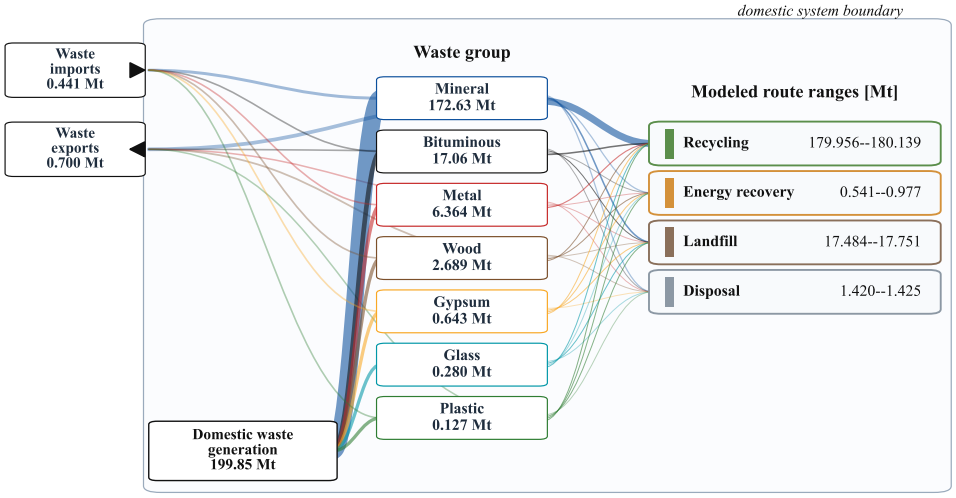
Domestic production results in 88.09 Mt $CO_2$e, compared with 84.55 Mt $CO_2$e from domestic consumption. The lower consumption-based value reflects GWP associated with exports exceeding that associated with imports. It is higher than the 69.58 Mt $CO_2$e reported by Volk (2024) for 2008, but close to the approximately 90.7 Mt $CO_2$e estimated for building materials in 2014 (BBSR 2020). The substantially lower estimate of approximately 30 Mt $CO_2$e by Rheude and Röder (2022) reflects their focus on annual changes in the anthropogenic building stock rather than total annual production and consumption.

End-of-life emissions remain largely absent from previous German building-sector assessments. In the present model, c2–c4 causes approximately 6.66 Mt $CO_2$e from a consumption-based perspective, corresponding to 1.9% of the gross annual footprint. In 2022, the consumption-based balance of non-hazardous construction and demolition waste amounted to approximately 199.59 Mt, derived from 199.85 Mt of domestic waste generation, 0.44 Mt of imports, and 0.70 Mt of exports. Hazardous CDW of 8.2 Mt is excluded.

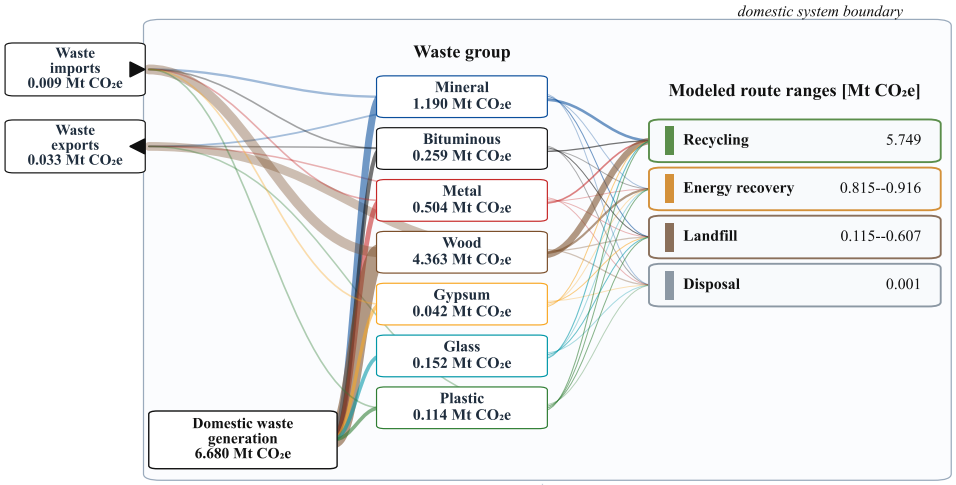
Figure 5(a) shows that end-of-life mass flows are dominated by mineral waste at 172.63 Mt, followed by bituminous waste at 17.06 Mt. Recycling clearly dominates the modeled treatment routes, accounting for approximately 180 Mt. However, the mass distribution alone does not indicate the main climate impacts.

Accordingly, panel (b) shows a markedly different emissions profile. Wood causes the highest c2–c4 emissions at 4.36 Mt $CO_2$e despite its comparatively small mass, whereas mineral waste contributes only 1.19 Mt $CO_2$e. Metals contribute 0.50 Mt $CO_2$e and bituminous waste 0.26 Mt $CO_2$e. End-of-life priorities therefore cannot be derived from waste quantities alone, but require material- and treatment-specific GHG factors.

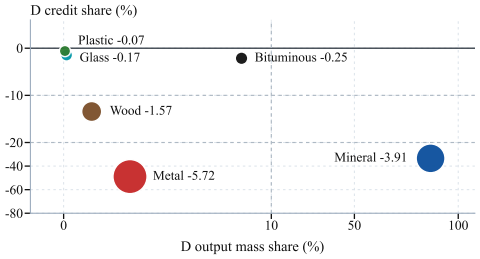
**(a) Waste mass generation and end-of-life processes**




**(b) $CO_2e$ emissions from end-of-life processes**




**(c) Module D credit matrix: mass share vs. credit share**




**(d) Route composition of largest D credits**

| Material | Recycl. | Energy | Landfill | Disposal |
|---|---|---|---|---|
| Metal | 100% | – | – | – |
| Mineral | 91% | – | 9% | – |
| Wood | 81% | 19% | – | – |
| Bituminous | 98% | – | 2% | – |
| Glass | 94% | – | 6% | – |
| Plastic | 94% | 4% | 2% | – |

**Fig. 5** Annual end-of-life activities and beyond-system effects in 2022: (a) waste generation, trade flows, and modeled treatment-route ranges, (b) corresponding c2–c4 GHG emissions, (c) potential Module D credits by material group, and (d) treatment-route composition of the largest credits. Reuse activity d1.1 is excluded.

Panels (c) and (d) present potential effects beyond the system boundary. Reuse (d1.1) is excluded because it is not reported at product or component level. Metals generate the largest potential credit of −5.72 Mt $CO_2$e despite their comparatively small mass, followed by mineral waste at −3.91 Mt $CO_2$e and wood at −1.57 Mt $CO_2$e. This demonstrates that high material throughput does not necessarily result in proportionally high substitution benefits. Recycling accounts for 100% of the metal credit and 91% of the mineral-waste credit, while energy recovery contributes 19% of the wood credit. These percentages describe the composition of the modeled Module D credits rather than observed treatment rates.

Overall, d1 yields a potential credit of −11.74 Mt $CO_2$e and is reported separately because substitution may occur in other sectors, countries, or years and depends on ÖKOBAUDAT allocation and system-modeling assumptions. Of 75.3 Mt of recycled mineral construction materials in 2022, only 14.5 Mt entered asphalt and concrete production (Bundesverband Baustoffe – Steine und Erden e.V. 2024). Recycling rates alone therefore do not demonstrate closed-loop substitution and should be complemented by indicators of material quality, actual substitution, and final use.

## 4.3 Annual GHG emissions from Construction and Deconstruction Activities

Annual construction and deconstruction activities (a4–a5) caused 9.93 Mt $CO_2$e in 2022, corresponding to 2.7% of the gross annual BCRE carbon footprint. The calculation includes 122.84 PJ of directly attributable construction-related energy use and excludes 78.67 PJ of stationary company energy, because these flows cannot be assigned directly to on-site construction or deconstruction processes. The included and excluded energy carriers, emission factors, and resulting construction-process emissions are documented in the Supplementary Information S3.8.

The magnitude is close to the 10.35 Mt $CO_2$e reported by BBSR (2020). However, the underlying national activity data are aggregated at construction-sector level and therefore do not distinguish whether the energy use is related to transport to construction sites, construction and installation processes, deconstruction, maintenance, repair, replacement, or refurbishment.

Figure 6a shows that diesel dominates both final energy use and emissions. Diesel accounts for 65.5% of included final energy demand and causes 5.95 Mt $CO_2$e, corresponding to 59.9% of a4–a5 emissions. Electricity follows with 13.3% of final energy use but 2.52 Mt $CO_2$e, or 25.4% of emissions.

Figure 6b compares the energy and emission shares by carrier and shows the same imbalance more explicitly. Electricity has a substantially higher emission share than energy share, reflecting the carbon intensity of the 2022 German electricity mix. Diesel and electricity together account for 85.2% of a4–a5 emissions, indicating that mitigation is concentrated in reducing diesel-based mobile machinery use and in decarbonizing construction-site electricity.

Natural gas and gasoline contribute 0.80 and 0.55 Mt $CO_2$e, respectively, while biodiesel and bioethanol contribute 0.11 Mt $CO_2$e. Biodiesel and bioethanol account for 4.8% of included final energy use but only 1.1% of emissions because of their lower assigned GWP factors. Overall, non-electric fuels account for 74.6% of

construction-related emissions, confirming that mobile fossil-fuel use remains the principal mitigation priority despite the comparatively small contribution of a4–a5 to the total annual BCRE footprint.

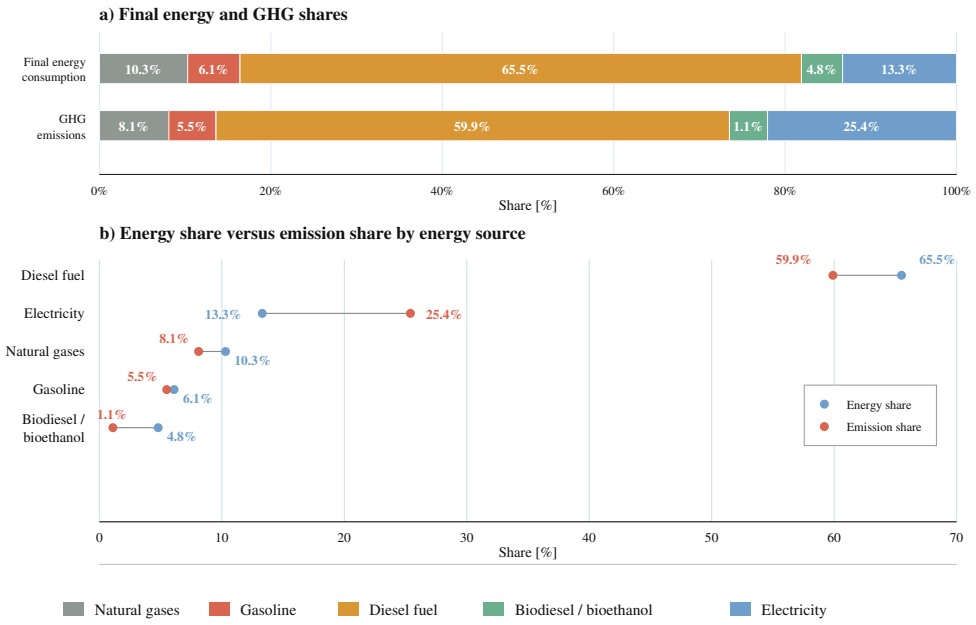



**Fig. 6** Final energy use and GHG emissions from construction and deconstruction activities in 2022: (a) energy and emission shares by energy carrier and (b) comparison of energy and emission shares.

## 4.4 Annual Building Use and Operation Emissions

Building use and operation dominate the climate impact of Germany's BCRE sector. In 2022, operational energy use (b6) caused 259.8 Mt $CO_2$e, of which 179.4 Mt $CO_2$e originated from residential buildings and 80.4 Mt $CO_2$e from non-residential buildings. Together, b6 accounts for 71.6% of the total BCRE footprint. Including operational water use (b7), the share increases to 72.1%. The underlying input data for operational energy and water use are documented in Supplementary Information S2.7 and S2.8, while the corresponding result workbooks are documented in S3.9 and S3.10.

The operational share is comparable to the 74.6% reported by BBSR (2020) and the 71.0% reported by Volk (2024). This confirms that near-term mitigation remains strongly dependent on reducing building energy demand and decarbonizing heat and electricity supply.

Residential buildings are the main source of b6 emissions, as shown in Figure 7(a), with 179.4 Mt $CO_2$e, corresponding to 69% of operational energy emissions. Within the non-residential stock, commerce, trade, and services (GHD) contribute 63.7 Mt $CO_2$e,

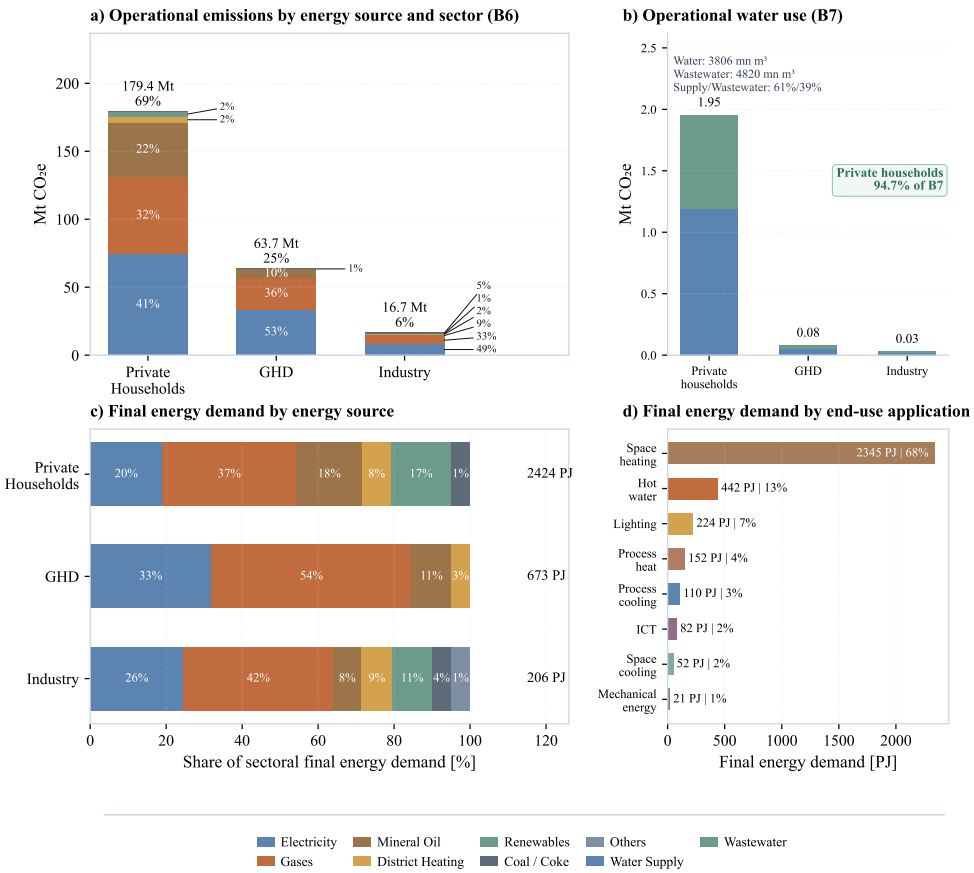



**Fig. 7** Annual GHG emissions associated with building use and operation in 2022. Panel (a) shows b6 emissions by energy carrier and sector, panel (b) b7 emissions, panel (c) b6 final energy demand by carrier, and panel (d) b6 final energy demand by end-use application.

while industry contributes 16.7 Mt $CO_2$e. This indicates that mitigation strategies must address both residential heat demand and the electricity-intensive operation of service-sector buildings.

Operational water use (b7) contributes 2.06 Mt $CO_2$e and is therefore secondary compared with b6. Panel (b) shows that b7 emissions are concentrated in private households, which account for 94.7% of b7 emissions. The underlying water and wastewater volumes amount to 3,806 million $m^3$ of drinking water and 4,820 million $m^3$ of wastewater.

The final energy-demand structure differs strongly by sector, as shown in Figure 7(c). Residential buildings are dominated by gases and mineral oil, while electricity plays a larger role in GHD and industry. In the emissions perspective shown in panel (a), electricity contributes disproportionately to b6 emissions: 41% in residential buildings, 53% in GHD, and 49% in industrial building-related emissions.

Carrier-specific GHG intensity is therefore as important as absolute energy demand when identifying mitigation priorities.

Panel (d) shows that space heating is by far the largest end-use application, accounting for 2,345 PJ or 68% of operational final energy demand. Domestic hot water follows with 442 PJ or 13%, and lighting with 224 PJ or 7%. Operational emissions are therefore primarily driven by heat demand, fossil fuel use, and the carbon intensity of electricity. Effective mitigation requires a combined strategy of building-efficiency improvements, electrification based on low-carbon electricity, and decarbonization of district-heating systems.

# 5 Limitations

The framework is subject to several limitations arising from its annual national accounting perspective and the granularity of the underlying data. It represents annual national activities rather than specific buildings, components, or interventions. Production and trade statistics identify product categories but not their final applications, preventing A1–A3 flows from being differentiated by building type, infrastructure, or construction activity. Apparent domestic consumption also excludes inventory changes and time lags between production, installation, and disposal. Aggregated energy data preclude separate estimates of A4, A5, and C1, while missing component-level stock data prevent the independent quantification of B2–B5. The results therefore characterize annual market activity and sector-wide hotspots, but not physical stock changes or emissions from individual building types and measures.

A major source of uncertainty is the scaling of EPD data to national product flows. EPDs represent specific products, technologies, declared units, background datasets, and modeling assumptions rather than national average emission factors (DIN 2022; BMWSB 2024). The mapped datasets are assumed to represent the corresponding products supplied to the German market, although their actual market shares are unknown. Differences in allocation, reference units, background systems, biogenic carbon accounting, end-of-life scenarios, and Module D modeling remain embedded in the published datasets. For example, in cement production, impacts associated with waste-derived fuels may be allocated partly to the waste-generating system rather than to the cement product, while the treatment of biogenic carbon depends on the applied accounting rules. Such choices can shift burdens between product systems and produce different cement-related GHG factors under alternative system models. The automated workflow makes the selection and calculation reproducible, but cannot eliminate these source-data uncertainties. Results for A1–A3, C2–C4, and D1 therefore represent standardized national estimates rather than measured product-specific emissions.

This uncertainty is particularly pronounced for end-of-life treatment because route-specific ÖKOBAUDAT factors are available for only a limited share of the mapped products. Standard-scenario and generic factors are therefore frequently applied, reducing the treatment-route specificity of C2–C4. Domestic treatment shares are also assigned to imported and exported waste because route-specific trade data are unavailable. Hazardous CDW and reuse are excluded because they cannot be represented

consistently using the available factors and statistics. The C2–C4 results consequently describe average non-hazardous waste treatment rather than a complete route-resolved national balance.

A further limitation is that the assessment reflects observed activities and treatment practices in 2022 rather than technically achievable mitigation. The D1 results describe conditional substitution effects whose timing, location, and magnitude depend on secondary-material quality, the substituted primary process, and the allocation assumptions embedded in the EPDs. They therefore do not represent reductions necessarily realized in 2022 or attributable exclusively to the BCRE sector. Moreover, the reported GHG results may differ from other system assessments where recycling and waste-treatment burdens or credits are allocated to different product systems or life-cycle stages.

Finally, the environmental scope is restricted to GWP-total. Potential trade-offs and co-benefits related to resource use, toxicity, land use, water use, and other impact categories are not captured. A lower carbon footprint therefore does not necessarily indicate a lower overall environmental impact.

# 6 Conclusion and Recommendations

The results show that whole-life carbon accounting of the BCRE sector requires an integrated framework covering annual activities across production, construction, use, end-of-life, and beyond-system effects. The hybrid approach demonstrates that this is feasible with existing statistical infrastructures despite remaining classification and data inconsistencies.

Cross-sectoral GHG accounting should therefore be institutionalized through a dedicated thematic EEA account (BBSR 2020; Volk 2024). Such an account could support annual BCRE monitoring, mitigation and policy assessment, and alignment with KSG targets (Kaya et al. 2026), while complementing source-based reporting by making distributed responsibilities and burden shifting visible. The following methodological developments are particularly important.

1. **Standardized data selection and validation.** ÖKOBAUDAT should provide machine-readable metadata on module completeness, dataset representativeness, exclusions, fallback levels, and outlier status for A1–A3, C2–C4, and Module D (BMWSB 2024). This would reduce manual interpretation and improve reproducibility across reporting years.
2. **Integrated classification concordances.** Production, trade, waste, and life-cycle data require harmonized concordance layers linking GP, WA, EAV, and ÖKOBAUDAT classifications. Production and trade statistics should consistently support the calculation of domestic production, imports, exports, and apparent domestic consumption (Destatis 2025b,a, 2021). Waste generation and treatment data should likewise be linked to cross-border waste flows (Destatis 2026; UBA 2022b,a).
3. **Differentiation by final construction application.** Product flows should be assignable to residential and non-residential buildings, infrastructure, new construction, renovation, replacement, and deconstruction. Current statistics classify

products by commodity rather than final use, preventing a robust allocation of a1–a3 emissions to individual BCRE activities.

4. **Improved construction-energy allocation.** Energy balances should distinguish construction-sector demand by activity, including new construction, renovation, refurbishment, and deconstruction (AGEB 2023; AG Energiebilanzen e.V 2024). Separate reporting of mobile machinery, temporary site electricity, transport, and stationary company energy would improve the allocation of a4, a5, and c1.
5. **More detailed operational-energy accounts.** Application balances should distinguish building-related services from user- and process-related energy use in accordance with DIN EN 15978:2026-09. This would allow b6.1, b6.2, and b6.3 to be quantified separately rather than aggregated across space heating, building services, appliances, ICT, cooking, and process energy (AGEB 2023; AG Energiebilanzen e.V 2024).
6. **Component-level building-stock data.** Independent estimates of maintenance (b2), repair (b3), replacement (b4), and refurbishment (b5) require component-level information on material quantities, service lives, replacement cycles, and renovation activities. Material passports, building resource passports, digital product passports, and digital building logbooks could support this data infrastructure, although their current coverage and interoperability remain insufficient for representative national accounting (Heinrich and Lang 2019; DGNB 2026; European Parliament and Council of the European Union 2024b,a).
7. **Material-specific end-of-life reporting.** Waste statistics should distinguish mono-material, composite, and multi-component products and report treatment routes by material and product group (Destatis 2026). Data on reuse, recycling, energy recovery, landfill, backfilling, secondary-material outputs, substitution ratios, quality losses, and process losses are required to reduce reliance on generic C2–C4 and Module D factors and to clarify the actual fate and substitution potential of recovered materials (BMWSB 2024).
8. **Prospective mitigation scenarios.** Beyond annual monitoring, the observed 2022 baseline should be extended through prospective scenarios for product reuse, higher-quality recycling, and emerging treatment technologies. Examples include new recycling processes for autoclaved aerated concrete, higher-value uses of concrete fines, and other material-specific innovations. Such scenarios should combine technology-specific LCA data with assumptions on collection, processing yields, material quality, substitution rates, and market uptake to quantify technically achievable GHG reduction potentials.

The automated framework provides a reproducible basis for implementing these developments. Once the required concordances and reporting structures are established, annual input data can be updated while retaining the same allocation and calculation logic, enabling consistent monitoring of the BCRE sector over time.

**Supplementary information.** Supplementary information accompanies this article and includes the documented input data, ÖKOBAUDAT screening and classification mappings, module-specific calculation workbooks, and additional outlier and hotspot analyses.

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## Declarations

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**Ethics approval and consent to participate.** Not applicable.

**Consent for publication.** Not applicable.

**Data availability.** The data supporting the findings of this study are available in the supplementary information.

**Materials availability.** Not applicable.

**Code availability.** The code used for the analysis is available from the corresponding author upon reasonable request.

**Author contributions.**

## References

AG Energiebilanzen e.V: Anwendungsbilanzen zur Energiebilanz Deutschland: Endenergieverbrauch Nach Energieträgern und Anwendungszwecken. https://ag-energiebilanzen.de/wp-content/uploads/2023/11/AGEB_23p2.pdf

AGEB: Anwendungsbilanzen zur Energiebilanz Deutschland: Endenergieverbrauch Nach Energieträgern und Anwendungszwecken. https://ag-energiebilanzen.de/wp-content/uploads/2023/01/AGEB_22p2_rev-1.pdf

BBSR: Umweltfußabdruck Von Gebäuden in Deutschland: Kurzstudie zu Sektorübergreifenden Wirkungen des Handlungsfeldes Errichtung und Nutzung Von Hochbauten Auf Klima und Umwelt. Full institutional name: Federal Institute for Research on Building, Urban Affairs and Spatial Development. https://www.bbsr

.bund.de/BBSR/DE/veroeffentlichungen/bbsr-online/2020/bbsr-online-17-2020-dl.pdf

BMUV: The German Government's Climate Action Programme 2020. https://www.bmuv.de/fileadmin/Daten_BMU/Pools/Broschueren/aktionsprogramm_klimaschutz_2020_broschuere_en_bf.pdf

BMWSB: Bewertungssystem Nachhaltiges Bauen (BNB). Full institutional name: Federal Ministry for Housing, Urban Development and Building (2008). https://www.bnb-nachhaltigesbauen.de/

BMWSB: Qualitätssiegel Nachhaltiges Gebäude (QNG) - Informationsportal Nachhaltiges Bauen. Full institutional name: Federal Ministry for Housing, Urban Development and Building (2021). https://www.nachhaltigesbauen.de/austausch/beg/

BMWSB: Bilanzierungsregeln des QNG Für Wohngebäude, Stand 01.03.2023. (2023). Full institutional name: Federal Ministry for Housing, Urban Development and Building. https://www.qng.info/wp-content/uploads/2023/01/QNG_Handbuch_Anlage-3_Anhang-311_LCA_Bilanzregeln-WNG_v1-2.pdf

BMWSB: ÖKOBAUDAT: Online-Datenbank mit Ökobilanz-Datensätzen zu Baumaterialien, Bau-, Transport-, Energie- und Entsorgungsprozessen. ÖKOBAUDAT-Online-Datenbank (2024). https://www.oekobaudat.de/no_cache/datenbank/suche.html

Bundesverband Baustoffe – Steine und Erden e.V.: Mineralische Bauabfälle - Monitoring 2022: Bericht zum Aufkommen und zum Verbleib mineralischer Bauabfälle im Jahr 2022. 14. Monitoring-Bericht der Initiative Kreislaufwirtschaft Bau, Bundesverband Baustoffe – Steine und Erden e.V., Berlin (dec 2024). Kreislaufwirtschaft Bau; verantwortlich: Dr. Matthias Frederichs; Redaktion: Dr. Berthold Schäfer. https://www.iste.de/source/Newsletter/2024-12_Newsletter/2024_08a_PM_KWB_Monitoring22.pdf Accessed 2026-06-20

Destatis: Klassifikation der Wirtschaftszweige 2008 (WZ 2008), Stand: 20.04.2023. Federal Statistical Office, (2008). Federal Statistical Office. https://www.destatis.de/DE/Methoden/Klassifikationen/Gueter-Wirtschaftsklassifikationen/Downloads/klassifikation-wz-2008-3100100089004-aktuell.pdf

Destatis: Gegen"uberstellung der Meldenummern des GP, Ausgabe 2019 (GP2019) mit den Warennummern des WA, Ausgabe 2021 (WA2021). Excel-Tabelle (2021). https://www.destatis.de/DE/Methoden/Klassifikationen/Gueter-Wirtschaftsklassifikationen/Downloads/melde-warennummern-3200220219015.xlsx

Destatis: Areas of Use of Water for 2022. Environmental-Economic Accounting table used for sectoral drinking-water-use volumes (2022). https://www.destatis.de/EN/Themes/Society-Environment/Environment/Environmental-Economic-Accountin

g/raw-material-flows-water/Tables/use-of-water.html

Destatis: Kurzübersicht Abfallbilanz (2022). https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Umwelt/Abfallwirtschaft/Tabellen/abfallbilanz-kurzuebersicht-2022.html

Destatis: Public Waste Water Treatment Plants and Annual Quantity of Waste Water. Used for domestic and industrial sewage-water volume in the B7 wastewater calculation (2022). https://www.destatis.de/EN/Themes/Society-Environment/Environment/Water-Management/Tables/public-waste-water-treatment-and-disposal-aba-7k.html

Destatis: Public Water Supply in Germany, 1991 to 2022. Used as plausibility control total for B7 drinking-water volumes (2022). https://www.destatis.de/EN/Themes/Society-Environment/Environment/Water-Management/Tables/ww-01-rate-connection-water-supply-1991-2022.html

Destatis: Statistischer Bericht: Umweltökonomische Gesamtrechnung Im Überblick 2023. Excel-Tabelle. https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Umwelt/UGR/ueberblick/Publikationen/Downloads/statistischer-bericht-ugr-ueberblick-5850026239005.html

Destatis: Bruttostromerzeugung in Deutschland f"ur 2019 bis 2024 (2024). https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Energie/Erzeugung/Tabellen/bruttostromerzeugung.html

Destatis: Aus- und Einfuhr (Außenhandel): Deutschland, Jahre, Warenverzeichnis (8-Steller). GENESIS-Online-Datenbank (2025). https://www-genesis.destatis.de/datenbank/online/statistic/51000/table/51000-0013

Destatis: Produktion im Verarbeitenden Gewerbe: Deutschland, Jahre, Güterverzeichnis (9-Steller). GENESIS-Online-Datenbank (2025). https://www-genesis.destatis.de/datenbank/online/statistic/42131/table/42131-0004

Destatis: Statistischer Bericht: Umweltökonomische Gesamtrechnungen Im Überblick 2025. Stand: 20.10.2025. https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Umwelt/UGR/ueberblick/Publikationen/Downloads/statistischer-bericht-ugr-ueberblick-5850026259005.html

Destatis: Betriebe, erzeugte Abfallmenge: Deutschland, Jahre, Abfallarten, Tabelle 32161-0001 (2026). https://www-genesis.destatis.de/datenbank/online/statistic/32161/table/32161-0001

DGNB: Der Gebäuderessourcenpass der DGNB. Version 1.3, Stand: Überarbeitung Juni 2026. Zugriff am 29. Juli 2026 (2026). https://www.dgnb.de/de/nachhaltiges-bauen/zirkulaeres-bauen/gebaeuderessourcenpass

DIN: DIN EN 15804:2022-03: Sustainability of Construction Works – Environmental Product Declarations – Core Rules for the Product Category of Construction Products. German Institute for Standardization, (2022). German Institute for Standardization. https://www.dinmedia.de/de/norm/din-en-15804/344735627

DIN: EN 15978:2026. https://www.cencenelec.eu/news-events/news/2026/en-in-the-spotlight/2026-04-17-en-15978-2026/

EC: NACE Rev. 2: Statistische Systematik der Wirtschaftszweige in der Europäischen Gemeinschaft. Full institutional name: European Commission. https://ec.europa.eu/eurostat/documents/3859598/5902453/KS-RA-07-015-DE.PDF.pdf/680c5819-8a93-4c18-bea6-2e802379df86

EEA: Addressing the Environmental and Climate Footprint of Buildings. https://doi.org/10.2800/1800539 . Full institutional name: European Environment Agency. https://www.eea.europa.eu/en/analysis/publications/addressing-the-environmental-and-climate-footprint-of-buildings

European Parliament and Council of the European Union: Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings. Official Journal of the European Union, L 2024/1275, 8 May 2024. Recast (2024). https://data.europa.eu/eli/dir/2024/1275/oj

European Parliament and Council of the European Union: Regulation (EU) 2024/3110 of the European Parliament and of the Council of 27 November 2024 laying down harmonised rules for the marketing of construction products and repealing Regulation (EU) No 305/2011. Official Journal of the European Union, L 2024/3110, 18 December 2024 (2024). https://data.europa.eu/eli/reg/2024/3110/oj

Fraunhofer: Wastewater Treatment Electricity-Intensity Assumption. Used for B7 wastewater treatment electricity intensity; model applies 0.300 kWh/m3 as midpoint of the documented 0.2–0.4 kWh/m3 range (2022). https://publica.fraunhofer.de/bitstreams/402b8e21-255b-4dae-9948-a16315135180/download

Heinrich, M., Lang, W.: Materials Passports – Best Practice: Innovative Solutions for a Transition to a Circular Economy in the Built Environment. Technische Universität München, in association with BAMB, München (2019). https://doi.org/10.5281/zenodo.2556515

IPCC: Annex I: Glossary (2018). https://www.ipcc.ch/site/assets/uploads/sites/3/2019/11/SROCC_FD_AnnexI-Glossary_Final.pdf

KBOB, ecobau, IPB: Ökobilanzdaten im Baubereich 2009/1:2022, Version 6.2 (2024). https://www.kbob.admin.ch/de/oekobilanzdaten-im-baubereich Accessed 2026-07-18

Kaya, T., Volk, R., Schultmann, F.: Bridging scales and methods: A systematic review

of mitigation pathway modeling for germany's building and construction sector. Sustainable Cities and Society: Advances, 100049 (2026) https://doi.org/10.1016/j.scsadv.2026.100049

Lützkendorf, T.: The role of carbon metrics in supporting built-environment professionals. Buildings and Cities **1**(1), 676–686 (2020) https://doi.org/10.5334/bc.73

Rheude, F., Röder, H.: Estimating the use of materials and their GHG emissions in the german building sector. Cleaner Environmental Systems (2022) https://doi.org/10.1016/j.cesys.2022.100095 . Advance online publication

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., Wit, C.A., Hughes, T., Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Foley, J.: Planetary boundaries: Exploring the safe operating space for humanity. Ecology and Society **14**(2), 32 (2009) https://doi.org/10.5751/ES-03180-140232

Schiller, G., Müller, F., Ortlepp, R.: Mapping the anthropogenic stock in germany: Metabolic evidence for a circular economy. Resources, Conservation and Recycling **123**, 93–107 (2017) https://doi.org/10.1016/j.resconrec.2016.08.007

Schiller, G., Ortlepp, R., Krauß, N., Steger, S., Schütz, H., Acosta Fernández, J., Reichenbach, J., Wagner, J., Baumann, J.: Kartierung des anthropogenen lagers in deutschland zur optimierung der sekundärrohstoffwirtschaft. TEXTE 83/2015, Umweltbundesamt, Dessau-Roßlau (2015). https://www.umweltbundesamt.de/system/files/medien/378/publikationen/texte_83_2015_kartierung_des_anthropogenen_lagers.pdf

Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J.H., Theurl, M.C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., Tukker, A.: EXIOBASE 3: Developing a time series of detailed environmentally extended multi-regional input-output tables. Journal of Industrial Ecology **22**(3), 502–515 (2018) https://doi.org/10.1111/jiec.12715

UBA: ProBas Process Dataset: Xtra-Trinkwasser
DE-2000. Used for drinking-water supply energy intensity; 0.00216 MJ electricity per kg water, converted to 0.600 kWh/m3 (2000). https://data.probas.umweltbundesamt.de/datasetdetail/process.xhtml?uuid=611ff321-cdf7-456e-b8ae-a3016c1163b4

UBA: Grenzüberschreitende Verbringung von zustimmungspflichtigen Abfällen 2022 – Export (2022). https://www.umweltbundesamt.de/system/files/medien/10592/dokumente/grenzueberschreitende_verbringung_von_zustimmungspflichtigen_abfaellen_export_2022.pdf

UBA: Grenzüberschreitende Verbringung von zustimmungspflichtigen Abfällen 2022

– Import (2022). https://www.umweltbundesamt.de/system/files/medien/10592/dokumente/grenzueberschreitende_verbringung_von_zustimmungspflichtigen_abfaellen_import_2022.pdf

UBA: Emissionsbilanz erneuerbarer energieträger: Bestimmung der vermiedenen emissionen im jahr 2022. Technical Report Climate Change 49/2023, German Environment Agency (2023). https://www.umweltbundesamt.de/sites/default/files/medien/11850/publikationen/20231219_49_2023_cc_emissionsbilanz_erneuerbarer_energien_2022_bf.pdf

UBA: Treibhausgas-Emissionen in Deutschland (2024). https://www.umweltbundesamt.de/daten/klima/treibhausgas-emissionen-in-deutschland

UBA: Finale Daten für 2023: Klimaschädliche Emissionen sanken um zehn Prozent (2025). https://www.umweltbundesamt.de/presse/pressemitteilungen/finale-daten-fuer-2023-klimaschaedliche-emissionen

UNEP, GlobalABC: Global Status Report for Buildings and Construction 2025–2026. Technical report, United Nations Environment Programme (2026). https://www.unep.org/resources/report/global-status-report-buildings-and-construction-2025-2026 Accessed 2026-07-18

UN: Paris Agreement. Full institutional name: United Nations (2015). https://unfccc.int/sites/default/files/english_paris_agreement.pdf

UNEP: Global status report for buildings and construction: Beyond foundations – mainstreaming sustainable solutions to cut emissions from the buildings sector. Technical report (2023). https://doi.org/10.59117/20.500.11822/45095

Volk, R.: Der Beitrag der Bau- und Immobilienbranche am Treibhauseffekt sowie Potenziale und Strategien zu seiner Minderung. Stiftungslehrstuhl Ökonomie und Ökologie des Wohnungsbaus (2024). https://publikationen.bibliothek.kit.edu/1000171878

Wiedmann, T., Minx, J.: A definition of Carbon Footprint. In: Pertsova, C.C. (ed.) Ecological Economics Research Trends, pp. 1–11. Nova Science Publishers, Hauppauge, NY (2008)

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# Supporting Information: Complete data, result workbook, and figure documentation

This supplementary file documents the cleaned input data, all result workbooks, compact workbook-level content descriptions, and selected finished outlier-analysis and hotspot-analysis figures generated by the notebook. To avoid duplicate formats, hotspot figures are provided as PDF files only.

## S2 Input Raw Data

**Table 1**: Input raw-data workbooks and compact content description.

| File ID | File | Description and main contents |
|---|---|---|
| S2.1 | 00_Input_Source_Register.xlsx | Index workbook listing the active input files and their role in the framework workflow. |
| S2.2 | 01_OEKOBAUDAT_OBD_2024/OBD_2024_I_2026-05-11T16_15_26_cleaned_obd_filtered.xlsx | Single cleaned ÖKOBAUDAT input workbook containing product identifiers, product names, categories, declared units, reference masses, module-level GWP values, scenario information, and the scenario-resolution log used as LCA input. |
| S2.3 | 02_Destatis_Production_GP2019/42131-0004_en.xlsx | Destatis GP2019 production statistics with product codes, descriptions, reporting year, production value, mass, volume, piece-count quantities, and reported units. |
| S2.4 | 03_Destatis_Foreign_Trade_WA2021/51000-0013_en.xlsx | Destatis WA2021 foreign-trade statistics with commodity codes, descriptions, reporting year, import/export quantities, trade values, and units. |
| S2.5 | 04_GP2019_WA2021_Concordance/Reported_Commodity_Codes_3200220269015.xlsx | Official GP-WA concordance workbook, including metadata, dataset description, and the concordance table linking production codes with commodity codes. |
| S2.6 | 05_Construction_Activities_A4_A5/Construction_Activities.xlsx | A4-A5 input workbook containing construction-sector final energy consumption, included mobile fuel carriers, excluded stationary carriers, electricity demand, electricity mix, and emission-factor assumptions. |
| S2.7 | 06_Use_Operation_B6/Use_Operation.xlsx | B6 input workbook containing residential and non-residential final energy demand by carrier and application area, electricity and district-heating mix assumptions, renewable-energy assumptions, and emission factors. |
| S2.8 | 07_Water_Use_B7/Water_Use.xlsx | B7 input workbook containing drinking-water and wastewater volumes, sector allocation, treatment assumptions, process electricity intensities, and water-related emission-factor inputs. |
| S2.9 | 08_Waste_EAV_C2_C4_Module_D/01_CDW_Generation_EAV/End_of_Life_C_D.xlsx | Original construction and deconstruction waste workbook with EAV waste generation, disposal, recovery, and treatment-route quantities before cleaning. |
| S2.10 | 08_Waste_EAV_C2_C4_Module_D/01_CDW_Generation_EAV/End_of_Life_C_D_cleaned.xlsx | Cleaned non-hazardous CDW workbook with EAV material groups, treatment-route quantities, and domestic route shares used for C2-C4 and Module D. |
| S2.11 | 08_Waste_EAV_C2_C4_Module_D/02_Waste_Import_Export/Waste_Import_Export_2022.xlsx | Waste import/export workbook containing 2022 cross-border waste quantities used to convert domestic generation into consumed waste flows. |

# S3 Result Workbooks

## Method overview before result workbooks

### *OEKOBAUDAT outlier analysis*

First, an outlier analysis of the ÖKOBAUDAT database was conducted to identify representative datasets and to exclude non-representative entries before the mapping and calculation steps. Following the approach of Volk (2024), who restricts the outlier assessment to the production phase (A1-A3), the procedure was extended to the module values used in this study, including A1-A3, C2-C4, and D. Products were assessed by module and reference unit using GWP intensity values. Potential outliers were identified with the interquartile range (IQR) method and were only excluded after plausibility checks of the declared reference flow, product type, density for volumetric units, and technical complexity.

The current outlier workbook covers 3079 unique ÖKOBAUDAT products. It identifies 1059 statistical outlier candidates, of which 193 products are excluded as non-representative outliers. In addition, 17 generic end-of-life datasets and 256 raw-material datasets are removed to avoid double counting. After this ÖKOBAUDAT-only filtering step, 2613 products remain available for the subsequent mapping and selection workflow. The excluded outliers occur mainly in C2, A1-A3, D, C4, and C3, reflecting cases where complete technical systems or entries with unsuitable reference units would otherwise distort material-based emission intensities. The resulting screening and filtering overview is shown in Figure 1.

### *Mapping principle and classification matching*

The official classifications GP2019 (production statistics) and WA2021 (foreign trade statistics) are formally linked through the official concordance table provided by Destatis (2021), which establishes a standardized correspondence between production and commodity codes. ÖKOBAUDAT does not contain a statistical product classification compatible with GP2019, WA2021, or EAV waste codes. Therefore, ÖKOBAUDAT products were mapped to GP2019 production codes, WA2021 trade codes, and material specific as well as practical EAV waste categories. This mapping is required to link product-level LCA data with production, trade, and waste statistics without double counting.

The mapping workflow builds on the filtered ÖKOBAUDAT product set and the framework raw-data workbook. The framework raw-data workbook contains 1898 entries before the final calculation workflow, while the current mapping workbook contains 540 mapped product rows. These rows are linked to 177 distinct GP2019 production codes and 255 distinct WA2021 trade codes when split-code entries are counted separately. All mapped rows contain a GP2019 code, a WA2021 code, and both material specific and practical EAV assignments. The workbook also flags whether the selected WA2021 code is contained in the official GP-WA concordance; in the current mapping table this check is fulfilled for all mapped rows.

The mapping and validation procedure first removes raw-material and generic end-of-life entries that would create double counting. It then checks whether the declared ÖKOBAUDAT unit can be harmonized with the physical units reported in production

and trade statistics. Where units differ, conversion factors and reference masses are used in the subsequent harmonization workbook. Finally, production, import, export, waste, and emission-factor information are brought together in the final product table, which contains 540 calculation rows used for the material, disposal, and Module D1 result workbooks.

***Hotspot analysis and graphical outputs***

The workbook additionally creates hotspot analyses for the result modules. For A1–A3, products and material groups are ranked by material consumption and production-stage carbon footprint. For Module C, the same hotspot logic is applied to disposal-related mass flows and C2–C4 emissions. For Module D1, hotspot figures rank the mass base and potential recycling and recovery credits; carbon hotspots are sorted by absolute contribution while retaining the original sign of the Module D1 result. The current product-analysis, Pareto, hotspot, and outlier-analysis figures are provided separately from the result workbooks in Supporting Information S4.

**Table 2**: Result workbook contents summarized by workbook.

| Workbook ID | File | Description and main contents |
|---|---|---|
| S3.1 | `01_Framework_Raw_Data_Workbook.xlsx` | Framework raw product table containing the structured product-level starting dataset used before ÖKOBAUDAT filtering, mapping, and module calculations. |
| S3.2 | `02_OBD_Outlier_Analysis.xlsx` | ÖKOBAUDAT outlier screening workbook. It includes summary results, excluded outliers, retained candidates, removed raw materials, outlier explanations, and methodology documentation. |
| S3.3 | `03_OBD_Master_Dataset.xlsx` | Filtered ÖKOBAUDAT master dataset with retained products, scenario-assignment checks, GWP-assignment checks, link checks, and consistency checks. |
| S3.4 | `04_Code_Mapping_GP_WA_EAV.xlsx` | Classification and allocation workbook linking ÖKOBAUDAT products with GP2019 production codes, WA2021 trade codes, and EAV waste categories; also includes mass-flow allocation, waste-allocation logic, product-mass traceability, and method notes. |
| S3.5 | `05_Conversion_Factors_and_Harmonized_Masses.xlsx` | Conversion-factor workbook containing declared units, reference masses, conversion factors, and harmonized quantities used to align statistical quantities with EPD declared units. |
| S3.6 | `06_Final_OBD_Material_Trade_Waste_Carbon.xlsx` | Integrated final product table combining retained ÖKOBAUDAT datasets, classification mapping, production/trade/waste quantities, and module-level carbon-footprint summaries. |
| S3.7 | `07_Construction_Product_A1_A3.xlsx` | A1-A3 result workbook with construction-product mass flows, production-stage GHG results, quantity traceability checks, and summaries by product and material group. |
| S3.8 | `08_Construction_Activities_A4_A5_2022.xlsx` | A4-A5 construction-activity result workbook containing construction-sector electricity demand, direct fuel demand, included/excluded carriers, emission factors, and total construction-process emissions. |
| S3.9 | `09_Use_Operation_B6_2022.xlsx` | B6 operational-energy result workbook containing residential and non-residential final energy demand, carrier specific emission factors, electricity-mix and district-heating calculations, and operational energy emissions. |
| S3.10 | `10_Water_Use_B7_2022.xlsx` | B7 water-use result workbook containing drinking-water and wastewater volumes, process electricity intensities, electricity-mix factors, and operational water-use emissions. |

| Workbook ID | File | Description and main contents |
|---|---|---|
| S3.11 | 11_Disposal_C2_C4_Construction_Products.xlsx | C2-C4 disposal result workbook with final results, detailed calculations, material-group summaries, waste traceability checks, and method notes for route allocation, unit conversion, and fallback selection. |
| S3.12 | 12_Module_D_Construction_Products.xlsx | Module D result workbook reporting final potential credits and loads, detailed route-based calculations, summaries by material group, and EAV 170904 scenario-comparison sheets. |
| S3.13 | 13_Carbon_Footprint_Module_Overview.xlsx | Carbon-footprint overview workbook aggregating module-level GHG results, consumed-in-Germany totals, mass-flow overview, and group-level carbon and mass summaries. |

# S4 Current Result Figures

**Table 3**: Current result figures included in the supplementary package.

| Group ID | Figure group | Description and included files |
|---|---|---|
| S4.1 | Outlier analysis | Current ÖKOBAUDAT outlier screening and dataset-filtering figure. Included file: figures/outlier_analysis/obd_module_outlier_analysis.pdf. |
| S4.2 | Product and material-flow analysis | Current product-level material-flow and GWP total accounting figure for construction products in 2022. Included file: figures/product_analysis/construction_product_material_accounting_2022.pdf. |
| S4.3 | Aggregated hotspot profile | Current aggregated hotspot profile comparing mass and carbon contributions across A1-A3, Module C, and Module D. Included file: figures/hotspot_analysis/01_combined_aggregated_hotspot_profiles.pdf. |
| S4.4 | Pareto analysis | Current combined Pareto analysis identifying the product and material groups that dominate mass and carbon contributions. Included file: figures/hotspot_analysis/02_combined_pareto_analysis.pdf. |
| S4.5 | Hotspot matrix | Current combined hotspot matrix comparing relative hotspot patterns across A1-A3, Module C, and Module D. Included file: figures/hotspot_analysis/03_combined_hotspot_matrix.pdf. |

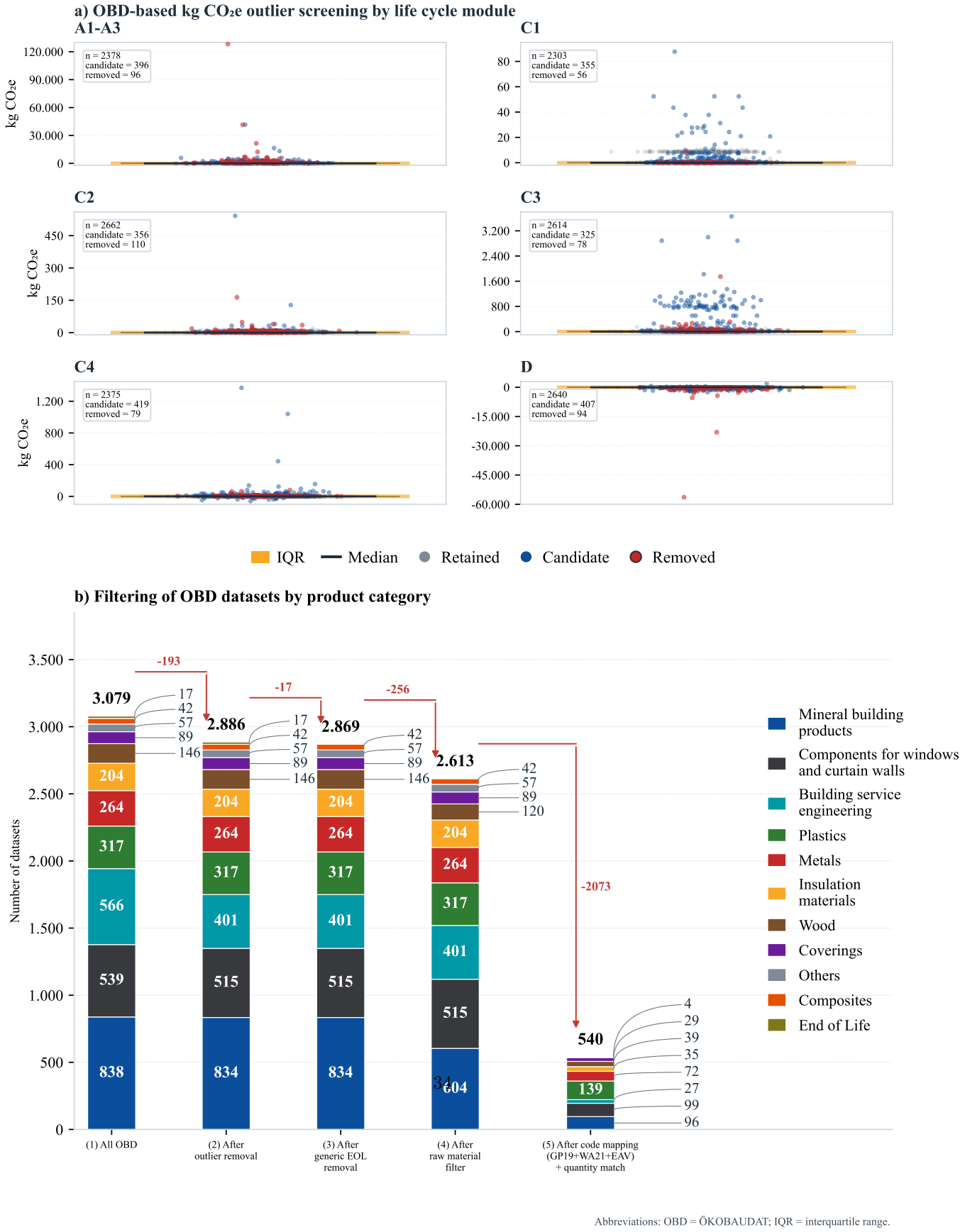



**Fig. 1** Outlier analysis: ÖKOBAUDAT outlier screening and dataset filtering.

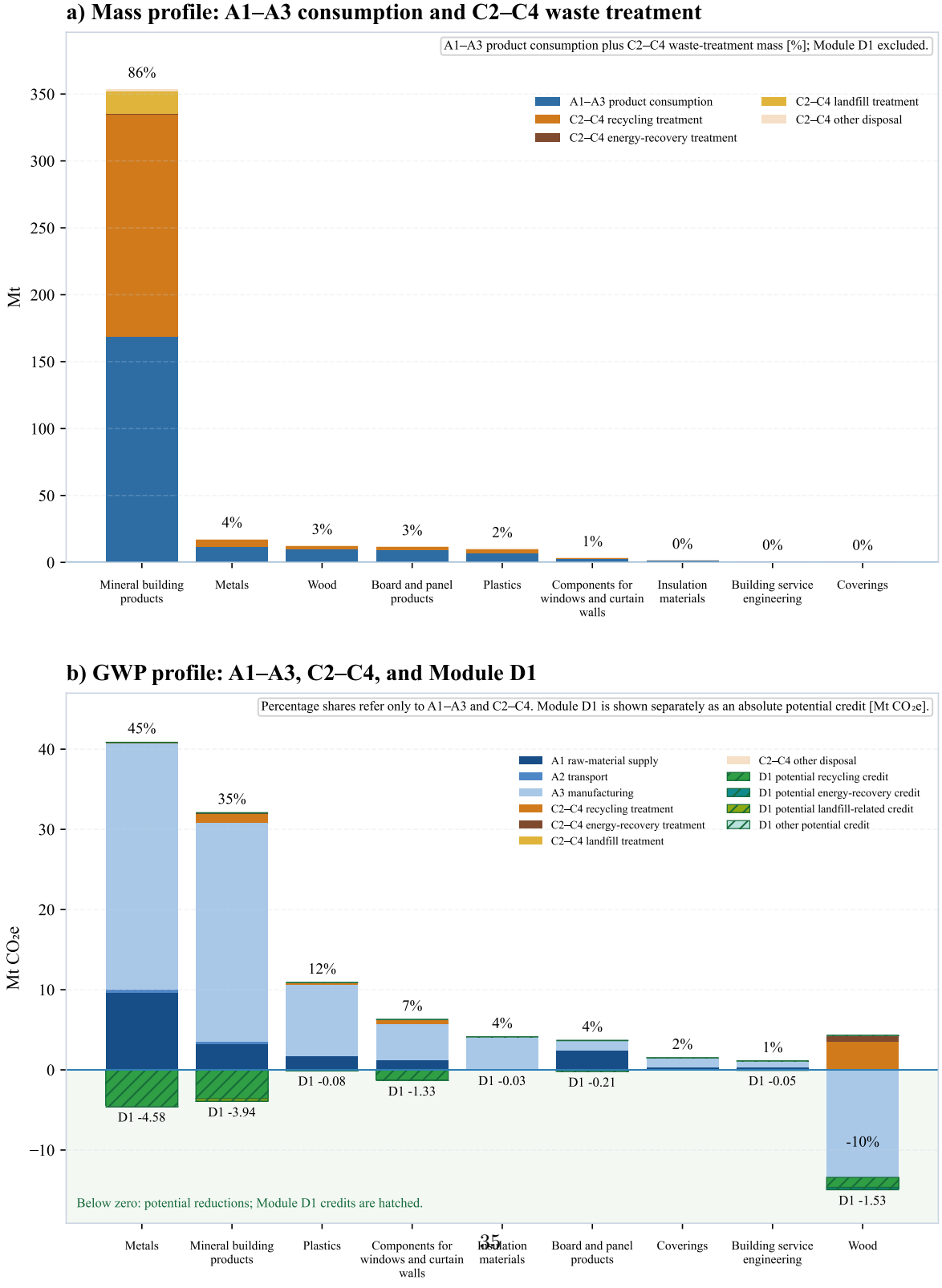



**Fig. 2** Aggregated hotspot profile comparing mass and carbon contributions across A1–A3, Module C, and Module D.

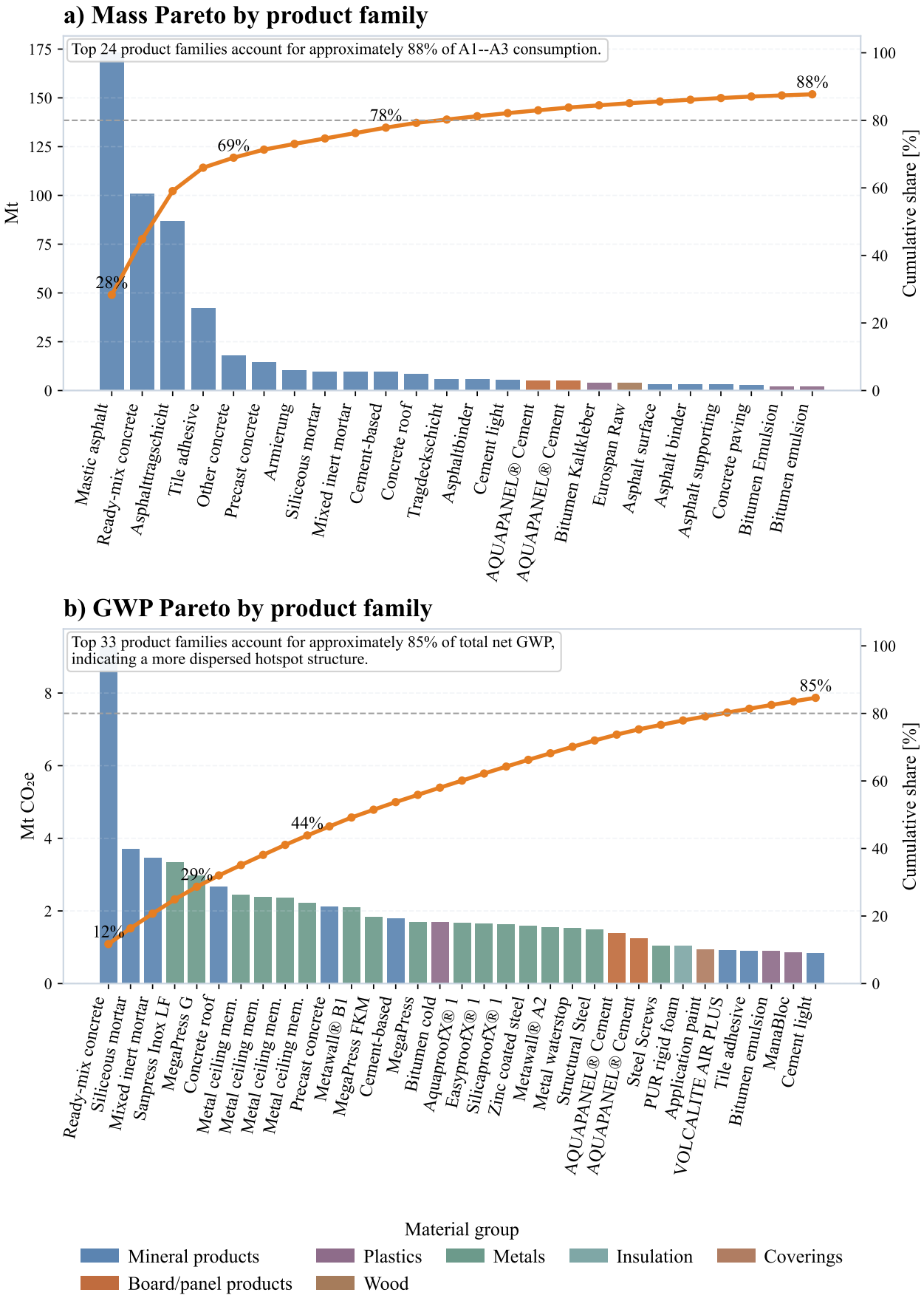



**Fig. 3** Combined Pareto analysis identifying the product and material groups that dominate mass and carbon contributions.

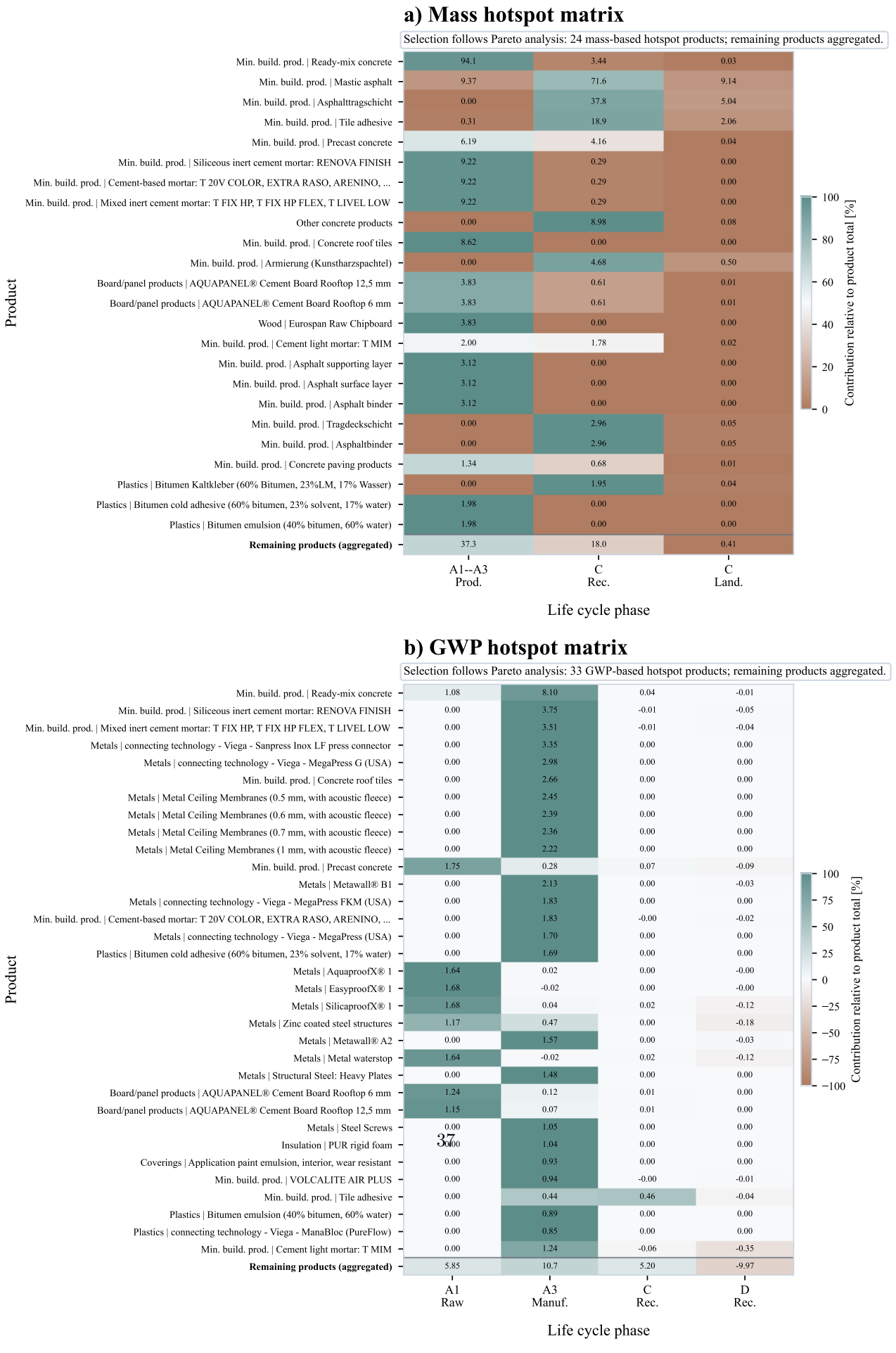



**Fig. 4** Combined hotspot matrix comparing relative hotspot patterns across A1-A3, Module C, and Module D.