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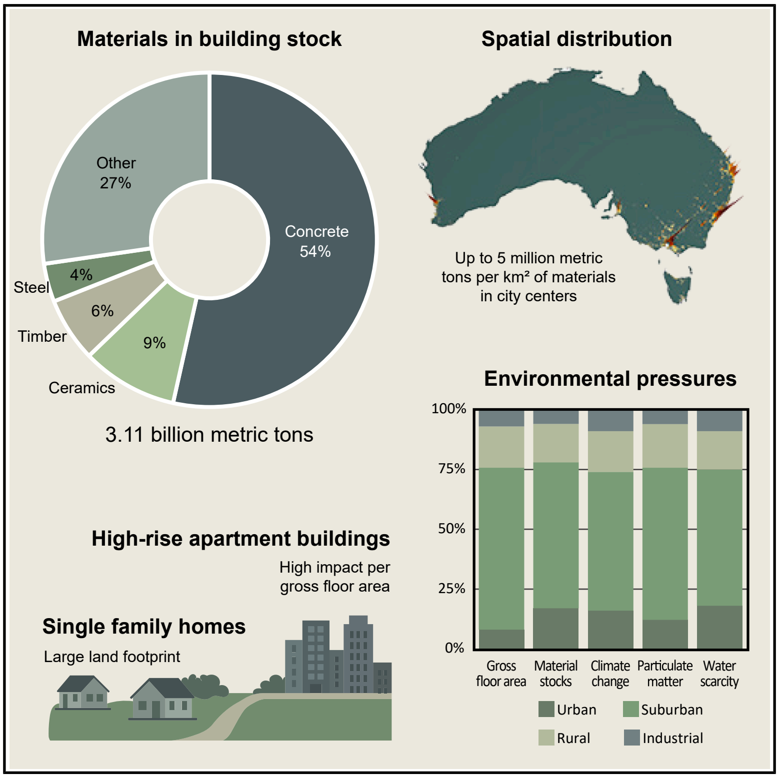
Embodied impacts of Australian building materials highlight trade-offs for sustainability policy

Graphical abstract



Highlights

- Concrete is 53% of the 3.11 billion tons of material in Australia's buildings
- High-rise buildings have the largest environmental impacts per gross floor area
- Material transport's environmental impact is low, except for sand and stone
- Urban areas have high material intensity, up to 5 million tons of material per km^2

Authors

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In brief

Analyzing 13.76 million Australian buildings, Marcos-Martinez et al. reveal a critical sustainability trade-off in urban design. Their findings show that while low-density single-family homes drive land-intensive urban sprawl, high-rise buildings concentrate environmental impacts due to their intensive use of steel and concrete. This trade-off underscores the need for spatially targeted policies, which balance the land-use impacts of suburbs with the material intensity of dense city centers. This approach can help reconcile the demands of urban growth with planetary health.

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Embodied impacts of Australian building materials highlight trade-offs for sustainability policy

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SCIENCE FOR SOCIETY The environmental impacts of building materials extend far beyond greenhouse gas emissions. Our analysis of 13.76 million structures reveals a staggering 3.11 billion metric tons of embodied materials—mostly concrete, steel, and timber—in Australian buildings, impacting resource extraction, pollution, and toxicity alongside carbon footprints. Single-family homes, dominant in sprawling suburban areas, demand vast land but have lower per-unit impacts, while high-rise towers in city centers concentrate energy-intensive materials, amplifying environmental burdens per square meter of gross floor area. These trade-offs show that urban growth strategies must balance density with sustainability. By mapping material stocks and impacts spatially, we provide a blueprint for planners and policymakers to rethink construction, prioritize circular material use, and design cities that thrive within planetary limits, ensuring healthier, more resilient communities for the future.

SUMMARY

The environmental footprint of the built environment extends far beyond carbon, yet urban planning often lacks the spatially explicit, multi-dimensional data needed to address the full scope of the planetary crisis. Analyzing 13.76 million Australian buildings via life cycle assessment, we quantify a 3.11 billion metric ton embodied material stock and assess impacts across resource depletion, pollution, and toxicity. Our findings reveal critical trade-offs in urban form: single-family homes have lower per-unit impacts but drive sprawl, while high-rise buildings conserve land but concentrate environmental burdens. Spatially, suburban areas account for the majority (~60%) of the total national impact, yet urban and industrial zones are hotspots for specific harms like mineral depletion and human toxicity. These results demonstrate that effective sustainability strategies for the built environment must be spatially targeted, deploying distinct policies to address the challenges of suburban scale versus urban intensity.

INTRODUCTION

The construction, use, disposal, and renewal of the building stock profoundly affect planetary health.[1] Building construction and operation influence a wide array of sustainability factors, including emissions, air and water quality, mental and physical health, social interactions, and resource sustainability at local and global scales.[2–4] While the built environment's contribution to climate change is well established,[5–8] representing over a third of global energy-related emissions,[9] its role in the interconnected crises of biodiversity loss and pollution, the "triple planetary crisis,"[10] is less understood. As ongoing energy transitions lower the operational carbon footprint of buildings, the embodied impacts from material production, i.e., from resource depletion and toxicity to ecosystem disruption, are becoming the next major frontier for sustainability policy. Addressing these broader impacts requires a holistic approach that moves beyond a focus on carbon emissions reduction.[11]

With urbanization and demographic change driving the demand for different building types, there is an urgent need to create sustainable built areas that meet societal needs at a low environmental impact.[12] This change requires the integration of sustainable practices into urban planning and construction processes,[13] which, in turn, depends on a clear understanding of material composition, spatial distribution, and the environmental footprint of buildings.

Recent analyses have begun to quantify wider environmental burdens. Studies on individual buildings have revealed that non-carbon impacts, such as biodiversity loss, disruptions in nitrogen and phosphorus cycles, ozone depletion, freshwater use, land-use change, and pollution, need to be considered for achieving sustainable built environments. For instance, a comparative life cycle assessment (LCA) of two residential buildings in Finland using two common database-software combinations (SimaPro/ecoinvent and GaBi) revealed significant inconsistencies when quantifying wider environmental burdens, with emission estimates showing the lowest variability.[14] To understand these impacts at a city or regional scale, a growing body of research integrates building material stock analysis with LCA.[15,16] For example, provincial-level analyses in China have shown that different structural material choices can alter a region's resource depletion footprint, with the results indicating that the intensive use of cement, steel, and concrete is the primary driver not only of fossil fuel depletion but also of human toxicity and global warming.[1] The impact of these choices is substantial, as embodied greenhouse gas (GHG) emissions from building materials grew to account for 24% of China's total emissions in 2015.[1] Similarly, a detailed analysis of Canberra's building stock indicates that the choice of urban development strategy itself introduces complex environmental trade-offs.[6] While a high-rise development scenario is optimal for reducing GHG emissions and land use, its greater reliance on steel results in a significantly higher embodied water footprint than lower-density options, highlighting the need for multi-faceted policy decisions.[6] These studies highlight the need for a multi-dimensional assessment of building materials, yet they often face two key limitations. First, they are typically limited in scope to individual buildings or precincts,[17] or they rely on aggregated statistical data that lacks high spatial resolution.[1] Second, comprehensive national-scale analyses that link specific building typologies, such as high-density vertical versus low-density horizontal forms, to a wide range of environmental trade-offs remain scarce. This results in a critical knowledge gap: urban planners and policymakers lack the detailed, spatially explicit evidence needed to design effective, long-term decarbonization roadmaps and targeted circular economy strategies for the built environment.[18]

Bridging this gap is essential because urban planning decisions have long-term, often irreversible consequences that shape resource consumption patterns for generations.[19] Without a quantitative understanding of material stocks and flows, policies aiming to decarbonize the built environment and mitigate broader pressures risk being inefficient and prone to unintended problem shifting.[20,21] A detailed spatial inventory of embodied construction materials is therefore a prerequisite for identifying opportunities for long-term sustainability.[8]

To address this gap, this study provides the first national-scale, spatially explicit assessment of the multi-dimensional embodied environmental impacts (EEIs) of Australia's building stock. By implementing a hybrid method that integrates building-specific data (e.g., boundaries, shape, and height) for 13.76 million buildings observed in Australia in 2023 with statistical information at the smallest geographical unit in the Australian census, statistical area level 1 (SA1), we provide a reproducible methodology for quantifying the material stocks and associated environmental burdens of an entire nation's building inventory. Australia presents a critical case study due to its sprawling, suburban-dominated development pattern,[22] which drives significant material demand, and its ambitious net-zero targets.[23] The 2023 data snapshot provides a baseline of cumulative historical impacts, establishing a foundation for future scenario analysis, strategic planning, and monitoring of policy impacts.[19]

We calculated the mass of embodied materials across all building types and, using a cradle-to-site LCA, quantified the environmental impacts of the extraction, processing, and transportation of 14 key construction materials to building sites, covering life cycle stages A1–A4. These LCA stages are becoming a larger share of the total life cycle impact.[6] This study demonstrates how spatially explicit material usage and impact data can inform integrated strategies for urban material circularity. Improving the environmental performance of building materials requires a comprehensive assessment of multiple environmental impacts rather than focusing on single sustainability targets. Adequate consideration of the long-term effects of building types and materials is essential for achieving sustainable, livable, and resilient cities.

RESULTS

Patterns of Australia's building stock and embodied materials

In 2023, Australia's building stock comprised approximately 13.76 million structures, providing an estimated 5.82 billion m^2 of gross floor area (GFA) (Figure 1A). Residential buildings dominated the stock, accounting for 94.6% of all structures and contributing about 5.05 billion m^2 of GFA, equivalent to 187 m^2 per capita. By contrast, commercial and industrial buildings represented smaller proportions of the total stock, accounting for 1.0% and 1.5%, respectively. These sectors contributed an estimated 207 million m^2 (8 m^2 per capita) and 258 million m^2 (11 m^2 per capita) of GFA. The remaining 2.8% of structures included mixed-use buildings and community facilities, collectively offering around 262 million m^2 (10 m^2 per capita).

Single-family homes (SHs) were the most prevalent building type, comprising approximately 12.46 million units and accounting for 4.7 billion m^2 of GFA. Low- to mid-rise apartments (1–3 stories) were the second most common, accounting for about 0.49 million buildings. All apartment buildings represented around 4% of the total building units and 6% of the GFA (340 million m^2). These findings highlight the dominance of residential buildings within Australia's built environment, with commercial and industrial sectors playing comparatively smaller roles. This pattern reflects the residential-centric nature of urban land use, where space allocation for non-residential functions remains relatively modest.

Australia's building stock is estimated to contain approximately 3.11 billion metric tons of materials, equivalent to 115 metric tons per capita (Figure 1C). Concrete, primarily used for slabs and multi-story buildings (Figure 1B), is the dominant material, accounting for 1.66 billion metric tons (53% of the total material mass). Unbound sand and stone, used for site preparation, foundations, and fill, are the second most prevalent materials. They contribute to 718 million metric tons (23%), followed

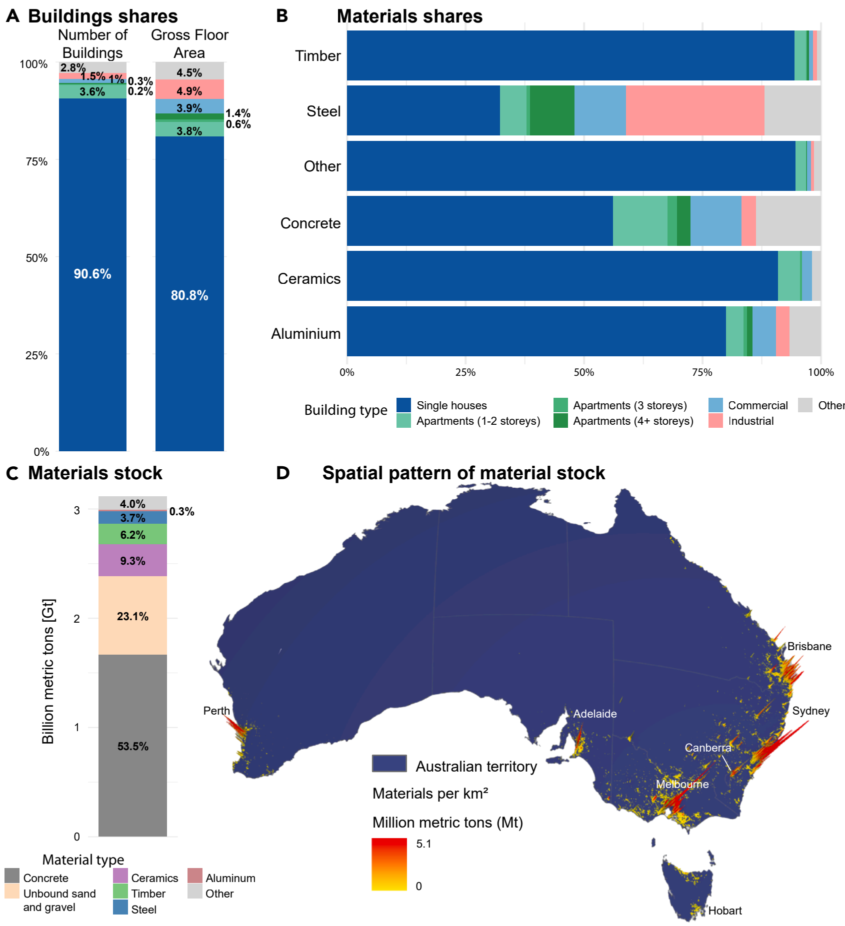

Figure 1. Composition of the Australian building stock in 2023, GFA by building type, material stock, and distribution

(A–D) Building shares: share of Australian buildings by count and gross floor area. (B) Materials shares: distribution of key construction materials across different building types showing the variation in material intensity per typology (e.g., the prevalence of timber in single houses versus steel in industrial buildings). (C) Materials stock: total accumulated material stock in billion metric tons (Gt) by material category. (D) Spatial pattern of material stock: geographic distribution and density of material stock across Australia, mapped as million metric tons (Mt) per km^2; the map is tilted to provide a three-dimensional visualization of stock accumulation in major coastal urban centers.

by ceramics (290 million metric tons, 9%), timber (192 million metric tons, 6%), and steel (114 million metric tons, 4%). The remaining materials, including plasterboard, glass, aluminum, insulation, bitumen, plastics, paint, carpet, and copper, each represent a small proportion of the total mass, collectively accounting for 4% of the building stock's material composition.

The spatial distribution of construction materials reveals pronounced urban concentrations, with significant peaks in metropolitan areas characterized by high-rise buildings. Business districts in cities such as Sydney, Melbourne, Brisbane, and Perth exhibit material intensities of around 5 million metric tons per square kilometer (Figure 1D). These urban hotspots reflect the high density of infrastructure and population. By contrast, regional and remote areas show considerably lower material stocks, emphasizing the disparity in resource utilization between urban and rural settings. This pattern highlights the uneven distribution of construction materials across Australia, with major cities concentrating the majority of material resources.

However, a material's contribution to total mass does not correlate with its environmental impact, as some low-mass materials have a disproportionate footprint (Figure S2). Aluminum, for instance, accounts for only 0.3% of the total mass but is the single largest contributor to freshwater ecotoxicity (36%) (Figure 2). Similarly, copper makes up around 0.04% of the mass but is responsible for some 10% of all mineral resource depletion and 13% of eutrophication impacts (Figure S2). Even plastics, at just 0.1% of the total mass, contribute a notable 2% to fossil fuel depletion and 1% of global warming potential (GWP). As such, effective policy must target materials based on their specific environmental impacts, not just their volume. The impact of materials like sand and stone is primarily concentrated in their transportation to construction sites. By contrast, materials such as steel, concrete, and ceramics contribute significantly to manufacturing-related impacts, including global warming and toxicity, despite their smaller share of the total mass. This distinction is critical for targeting decarbonization and other environmental policies. Hence, the rest of this paper focuses on construction materials with the greatest potential impact on sustainability transitions: concrete, ceramics, timber, steel, and aluminum.

Environmental footprint of Australia's building stock

We report environmental impacts of building materials across three main domains: resource use, air emissions and global warming, and toxicity and radiation, following established cradle-to-site LCA indicators.[24]

Resource use

The depletion of non-renewable abiotic resources associated with construction materials in Australia's building stock is estimated at 103,080 metric tons of antimony equivalents (tSbe), with steel contributing 59.6% and aluminum 11.7% of the total (Figure 2A). Fossil fuel depletion for the production and transportation of construction material amounts to 14.74 petajoules (PJ) of net calorific value (NCV), or 547 gigajoules (GJ) per capita, with ceramics accounting for the largest share (29.9%). This value corresponds to less than 1% of the fossil fuel energy consumed in Australia in 2023.[25] The building stock also embodies an estimated 8.34 billion m^3 of water, equivalent to 309 m^3 per capita, which is around 62% of the annual water consumption by

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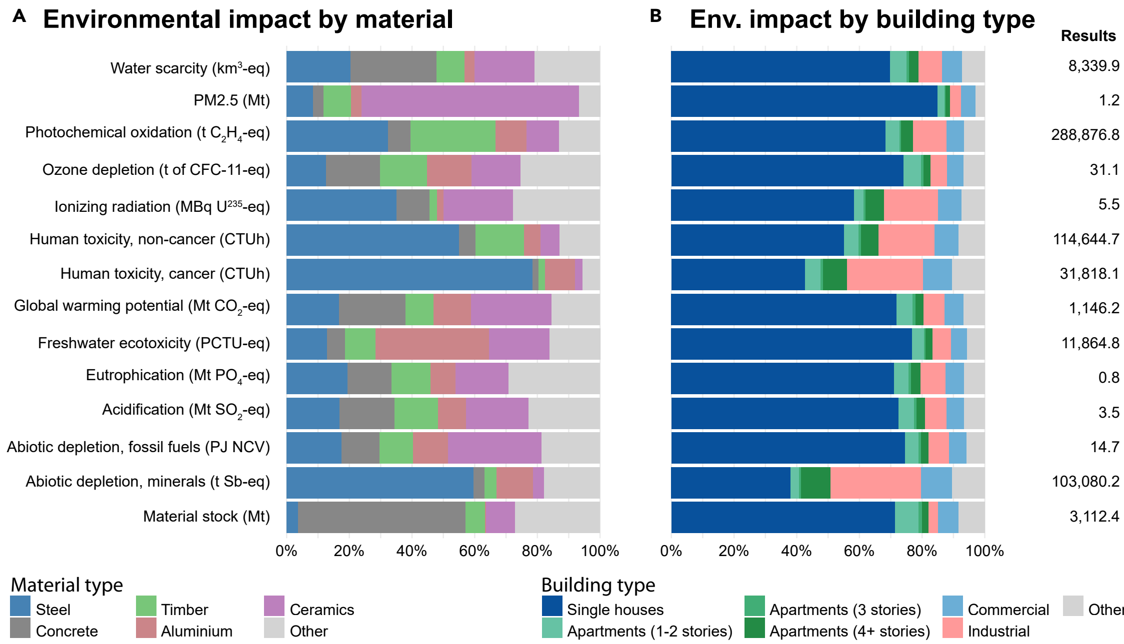

Figure 2. Proportional contribution of construction materials and building types to various environmental impact indicators

Shares of environmental impact by (A) material and (B) building types. Resource use: material stock, abiotic depletion of fossil fuels and minerals, and water scarcity. Toxicity and radiation: freshwater ecotoxicity and human toxicity (both cancer and non-cancer effects). Global warming and air pollution: all remaining indicators.

industries and households reported in 2021,[26] with concrete and steel accounting for 27.5% and 20.4%, respectively.

Global warming and air pollution

The embodied carbon footprint of construction materials in Australia's building stock is estimated at 1.2 billion metric tons of CO_2e, or 42.5 metric tons per capita, a value approximately 2.7 times Australia's total annual greenhouse gas emissions in 2023 (Figure 2A). The production and transportation of ceramics account for the largest share of embodied emissions at 25.8%, followed by concrete and steel with 21.2% and 16.8%, respectively.

Greenhouse gas emissions aside, the building stock represents a substantial cumulative stock of other embodied air pollution impacts. To contextualize these impacts, we compare our cumulative stock estimates to Australia's current annual national emissions flows. The embodied acidification potential is estimated at 3.5 million metric tons of sulfur dioxide equivalent (SO_2e), or 131 kg per capita. While a direct comparison is complex, this stock is equivalent to approximately 1 month of the nation's current annual acidification potential[27] The impact on eutrophication is even more significant, and the 0.84 million metric tons of embodied phosphate equivalent (PO_4e), 31 kg per capita, which corresponds to locking in 1.2 years of Australia's total national eutrophication.[27] The impact on particulate matter is the most pronounced. The 1.23 million metric tons of embodied particulate matter 2.5 (PM2.5) emissions represent a locked-in stock equivalent to 2.5 years of Australia's total annual PM2.5 emissions, with ceramics production accounting for 69% of this impact.[27] The photochemical oxidation potential (smog formation) associated with Australia's building stock is estimated at 289 thousand metric tons of ethylene equivalent (C_2H_4e), 11 kg per capita. Steel and timber production are the primary drivers, contributing 32.4% and 27% of the impact, respectively (Figure 2A). The ozone depletion potential is estimated at 31 metric tons of trichlorofluoromethane (CFC-11) equivalent (1.15 g per capita), with concrete and ceramics being the primary contributors with 17.3% and 15.6%, respectively. While the use of the most potent ozone-depleting substances is now banned under the Montreal Protocol, this historical stock represents a significant repository, with a potential impact equivalent to several years of Australia's remaining annual emissions from legacy equipment and materials. These findings show that the existing building stock represents a massive, multi-year repository of embodied pollution, highlighting the long-term consequences of material choices.

Toxicity and radiation

Freshwater ecotoxicity is estimated at 11,865 trillion comparative toxic units (CTUe), or 440 million CTUe per capita. Aluminum production and transport are the largest contributors to freshwater ecotoxicity at 36.4%, followed by ceramics (19.2%) and steel (12.8%) (Figure 2A). Human toxicity impacts, measured in comparative toxic units for human exposure (CTUh), are estimated at 32,000 CTUh for cancer effects and 115,000 CTUh for non-cancer effects, equating to 0.001 CTUh (cancer) and 0.004 CTUh (non-cancer) per capita. Steel production is the dominant contributor, accounting for 78.4% of cancer-related toxicity impacts and 55% of non-cancer effects. Ionizing radiation impacts are around 5.54 million mega becquerels (MBq) of Uranium-235 (U235) equivalents (0.21 MBq per capita), with steel (35%), ceramics (22.1%), and concrete (10.6%) generating the largest shares.

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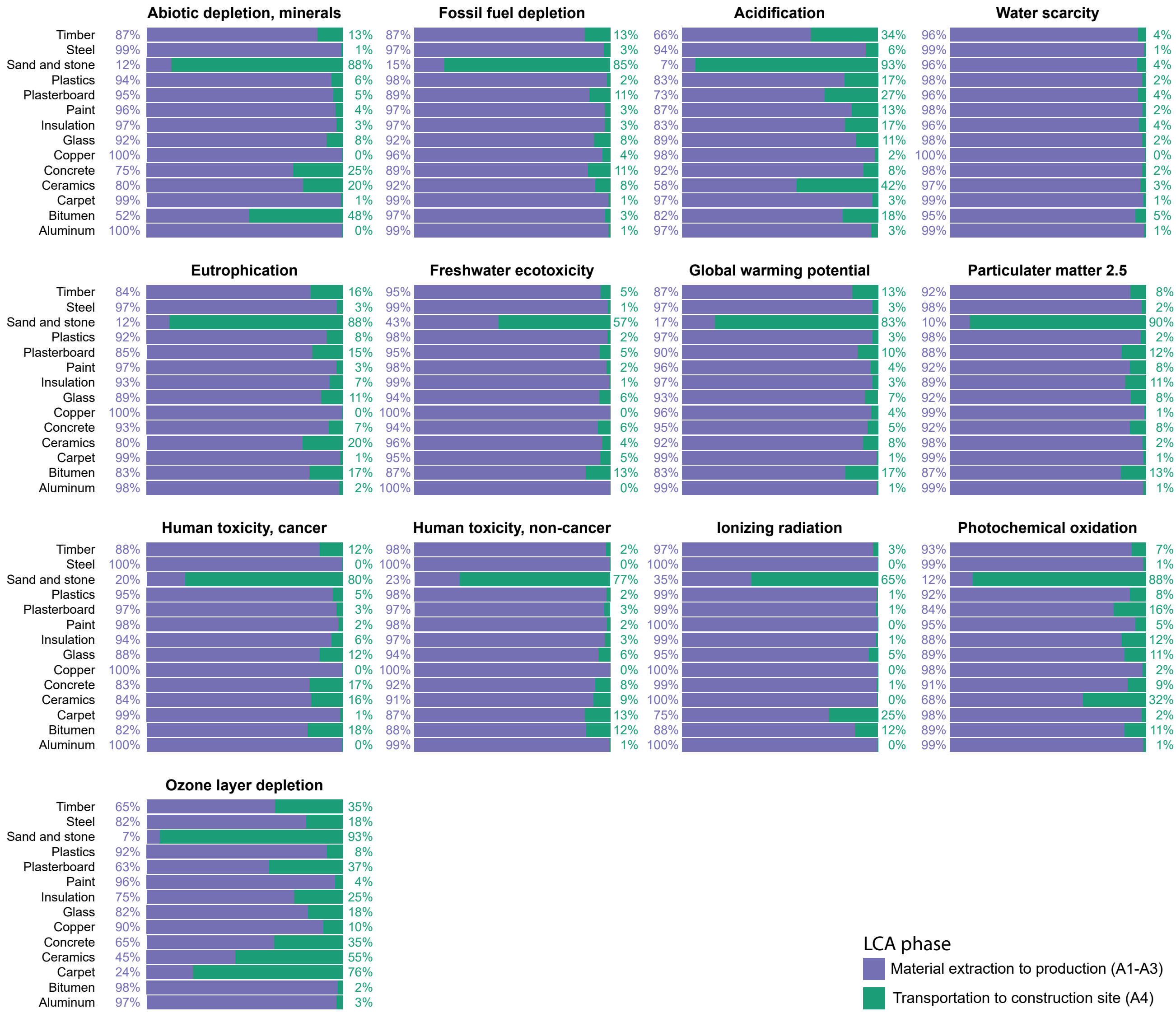

Figure 3. Relative contribution of material production (A1–A3) and transport (A4) stages to environmental impacts by material

Ceramics, steel, and concrete emerge as the most significant contributors across multiple environmental impact categories. Due to their dominance in Australia's building stock, SHs account for the largest share of environmental footprint across all indicators, with an average contribution of 66.3% across all impact categories (Figure 2B). Industrial buildings, characterized by their high reliance on metal components, rank as the second largest contributors to environmental impacts, accounting for approximately 11.4% on average.

The transportation of construction materials (A4) typically represents a small fraction of overall environmental impacts, with material production (A1–A3) dominating most indicator values (Figure 3). However, heavy or relatively unprocessed materials such as sand and stone stand out for their transport-related footprint, with over 80% of their abiotic resource depletion and fossil fuel use attributed to transportation. This reflects the mass-intensive nature of these materials and their relatively lower processing requirements upstream. Transport distances and logistics strategies thus play a critical role in shaping the EEIs of these materials. By contrast, highly manufactured inputs such as aluminum, copper, and steel register 90%–99% of their total environmental impacts during production, reflecting the energy-intensive processes required for extraction and refining.

Environmental footprint per GFA

While total stock assessments of the environmental footprint of embodied building materials provide valuable insights, they do not allow for a fair comparison of impacts across different building types. To provide comparable estimates, we normalized the environmental impacts by GFA for each building type (Figure 4).

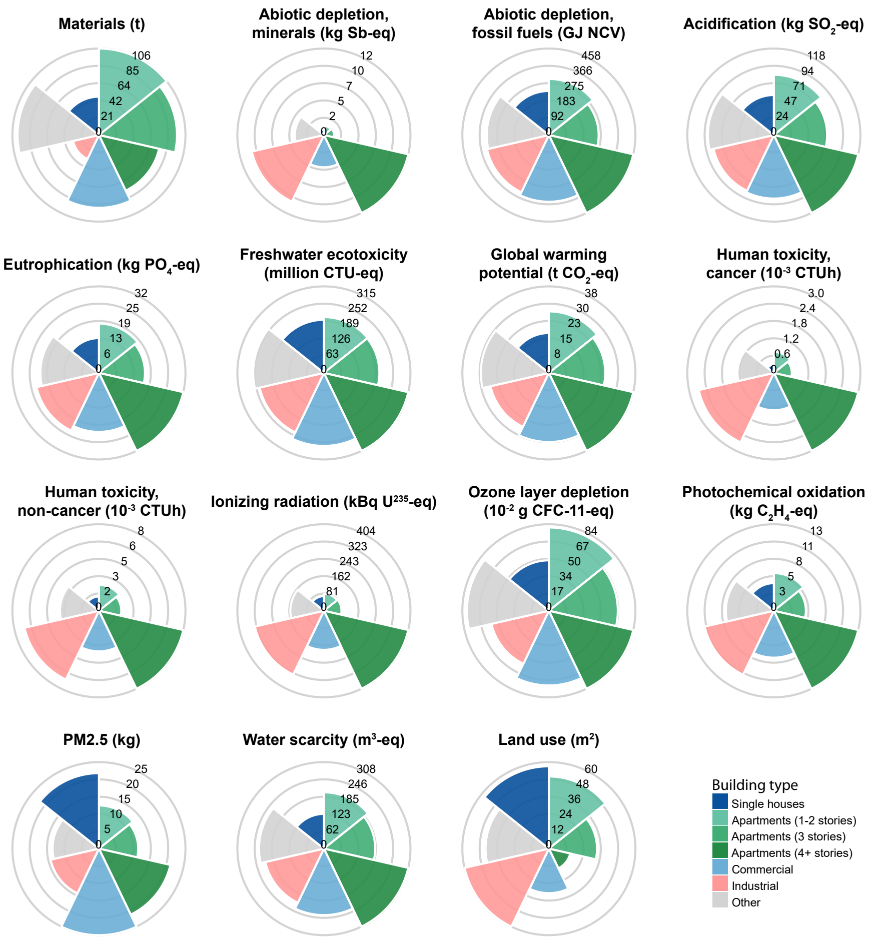

Figure 4. Environmental impact per 100 m^2 of GFA per major building type

Resource use

Material intensity, expressed as metric tons of material per 100 m^2 of GFA, varies significantly across building types. Low-rise apartments (1–2 stories) show the highest material demand at 106 tons (t) per 100 m^2, followed by mid-rise apartments (96 t) and high-rise apartments (76 t). Commercial buildings showed similar material intensity to mid-rise apartments at 89 t, whereas industrial buildings required substantially less material at 33 t per 100 m^2. SHs, on average, required 47 t per 100 m^2 of GFA, reflecting their lower structural complexity. High-rise apartments and industrial buildings also exhibit high abiotic depletion of non-renewable resources, with intensities of 12 and 10 kg Sb-e per 100 m^2, respectively, largely due to their reliance on metal-intensive construction practices. Fossil fuel depletion is highest in high-rise apartments, consuming 457 GJ per 100 m^2 of GFA, compared with 233 GJ per 100 m^2 for SHs.

Global warming and air pollution

High-rise apartments exhibit the highest GWP at 38 tCO_2e per 100 m^2 of GFA, followed by commercial buildings at 30 tCO_2e per 100 m^2. By contrast, SHs have the lowest embodied carbon at 18 tCO_2e. High-rise buildings also contribute the most to acidification (118 kg SO_2e per 100 m^2) and eutrophication (32 kg PO_4e per 100 m^2), highlighting their disproportionately high environmental burden relative to other building types.

Toxicity and radiation

Freshwater ecotoxicity impacts are highest for high-rise apartments, reaching 315 million CTUe per 100 m^2, indicating greater risks to aquatic ecosystems compared with other building types. Industrial and high-rise buildings have the highest human toxicity potential, with both cancer (0.008 CTUh per 100 m^2) and non-cancer effects (0.008 CTUh per 100 m^2). Ionizing radiation potential is also highest in high-rise. 404 kilobecquerels of U-235 equivalent (kBqU235e) and industrial buildings, 331 kBqU235e.

Land footprint

Significant trade-offs are evident across building typologies. SHs require the largest land footprint, averaging 57 m^2 of land per 100 m^2 of GFA, compared with just 15 m^2 per 100 m^2 for high-rise apartments. This contrast underscores the spatial efficiency of vertical development in urban environments, albeit at the cost of higher EEIs.[28] This extensive land footprint drives urban sprawl, contributes to habitat loss, and increases infrastructure demands, posing challenges to sustainable land management. For context, while the total land footprint of the national building stock, 318,000 ha, is around 1% of the 29 million hectares occupied by crops and horticulture in Australia,[28] its concentration in and around urban centers makes it a primary driver of high-impact land-use change.

Environmental footprint per capita

Normalizing impacts by occupants of residential buildings shows trade-offs of per-capita GFA, which varies from 122 m^2 for SHs and 110 m^2 for low-rise apartments to 74–79 m^2 for mid- and high-rise apartments.[29] Despite having the largest GFA, SHs have the lowest material intensity at 57.7 metric tons per person. Conversely, low-rise apartments require nearly double the material stock (116.6 t per capita). For embodied emissions, the trend shifts toward denser typologies. High-rise apartments exhibit the highest per-capita GWP at 29.8 tCO_2e, compared with 22.4 tCO_2e for occupants of SHs. This pattern, where denser living corresponds with higher embodied carbon intensity, holds across most environmental impact indicators (Figure S4).

These per-capita metrics are useful for assessing the national footprint of residential building types. The large contribution of SHs to Australia's total embodied impacts in buildings is generated by two interconnected factors: population housed in this typology and GFA allocation. Single houses provide shelter for approximately 90% of the Australian population (24.2 million residents)[30] and provide the largest per-capita GFA. Consequently,

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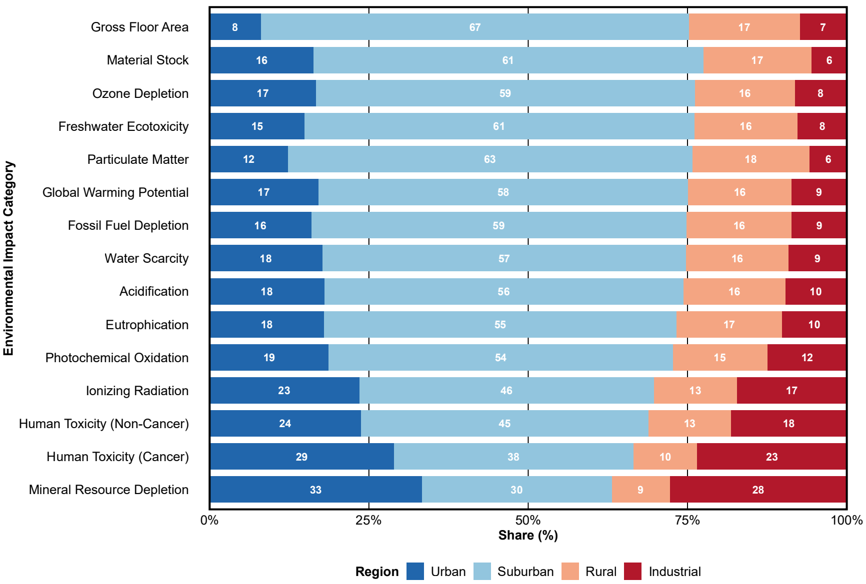

Figure 5. Environmental impact distribution across spatial development patterns

even modest per-capita impact rates in this typology, when aggregated across millions of buildings, result in the largest national environmental impact. This finding highlights the significant, locked-in consequences of Australia's sprawling, low-density residential development model.

Environmental footprint by spatial form

Distributing the environmental burden across different development patterns reveals that suburban areas are the dominant driver of Australia's total embodied impacts (Figure 5). This spatial form accounts for most EEIs, 61% of the material stock, and 58% of the GWP.

However, the environmental impact profile is not uniform. Urban and industrial zones, despite a smaller overall footprint, are hotspots for specific impacts linked to high-intensity construction and manufacturing. Urban cores, for instance, are the single largest contributor to mineral resource depletion (33%). Similarly, industrial areas account for a disproportionate share of human toxicity (cancer) (23%) and mineral resource depletion (28%). These findings underscore a critical trade-off: while suburban sprawl drives the bulk of the environmental load, urban and industrial intensification concentrates specific resource depletion and toxicity risks.

DISCUSSION

Our spatially explicit analysis of Australia's building stock reveals significant trade-offs between EEIs and land-use efficiency across different building typologies. High-rise apartments, prevalent in urban centers, exhibit elevated environmental impacts per unit area due to their reliance on energy-intensive materials such as steel and concrete. By contrast, SHs, which are dominant in Australia's suburban and rural landscapes, show lower per-unit impacts but contribute to extensive land use and urban sprawl. These findings, particularly when analyzed through the lens of distinct urban, suburban, and industrial development patterns, emphasize the critical need for sustainable material choices and integrated urban planning to support Australia's broad environmental goals.

Embodied materials and embodied CO_2e emissions in Australia's buildings

This study's findings indicate that the material composition of Australia's building stock closely aligns with global trends, with concrete, timber, ceramics (primarily bricks), and steel constituting the majority of material stocks.[8] These materials are fundamental to contemporary construction technology; however, their production is highly energy- and emissions-intensive, contributing significantly to resource depletion, carbon emissions, and pollution.[31,32] Although steel and ceramics represent a small proportion by mass, their production is associated with high energy demand and environmental toxicity and exacerbates resource depletion. These findings highlight the urgent need to transition toward low-impact materials, such as recycled aggregates, bio-based composites, and carbon-sequestering alternatives, which are increasingly recognized as essential for reducing the environmental footprint of urban development.[32,33]

The pronounced spatial disparities in building material distribution between urban and rural areas that we observed also reflect broader global patterns of uneven resource distribution. Major urban centers, including Sydney and Melbourne, exhibit material intensities exceeding 5 million metric tons per square km in some areas, primarily due to the prevalence of high-rise buildings. By contrast, rural and regional areas have significantly lower material stocks, reflecting less dense development patterns. These findings also show how a material's inherent properties, downstream supply chains, and production pathways drive substantial variability in both production- and transport-stage impacts. They highlight the need for context-specific mitigation strategies in Australia's building sector, including optimizing material sourcing, improving transport logistics, and increasing the use of lower-impact alternatives. We argue the need for spatially targeted policies to optimize material flows, implement circular systems, and align urban and regional development with planetary boundaries.[6]

Pathways to net-zero emissions need to account for baseline and projected spatial patterns of the built environment. High-density built-up areas have extensive material requirements but are more land- and energy-efficient than suburban developments.[34] On the other hand, suburban areas require extensive land use, dispersed infrastructure such as roads and sewage networks, and significant commuting requirements, increasing their impact on emission reduction targets.[35] These contrasting

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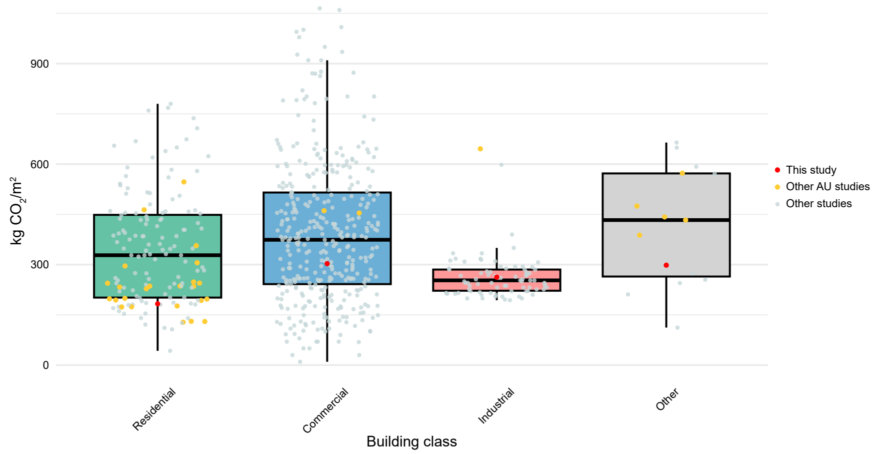

Figure 6. GWP from embodied construction materials per square meter of GFA by building type

dynamics highlight a need for tailored urban planning approaches that integrate efficient resource management, promote material innovation, and leverage spatial efficiencies to reconcile diverse typological challenges in achieving net-zero targets.

To contextualize our findings, we compare the embodied carbon intensity of Australia's building stock against international benchmarks (Figure 6). Embodied CO_2e in Australian buildings varies significantly across building types (Figure 6), reflecting disparities in construction technologies across building typologies. Our average estimate for residential buildings, 183 kg CO_2e/m^2, is less than the global average reported in previous studies,[36,37] 397 kg CO_2e/m^2, but falls within the range of Australian-specific analyses, 240 kg CO_2e/m^2. The wide variation in embodied carbon estimates across studies reflects regional differences in construction material composition, building practices, urban form, and energy sources.[37] For example, low-emission residential buildings in Europe and North America report embodied carbon levels of around 100 kg CO_2e/m^2 of GFA. By contrast, studies from China, Austria, and North America have documented values as high as 760 kg CO_2e/m^2.[36]

For commercial, industrial, and other building types, our estimated average embodied CO_2e per square meter of GFA is consistent with previous studies (Figure 6). While earlier research[36,38] estimates an average of 393 kg CO_2e/m^2 for commercial buildings, our analysis suggests a lower value of 303 kg CO_2e/m^2. However, the range of embodied carbon estimates is broad. The 2017 Embodied Carbon Benchmark Study V1[36] reports values spanning from 10 kg CO_2e/m^2 for commercial buildings in Europe to 1,065 kg CO_2e/m^2 for those in the Asia-Pacific region. Similarly, Huang et al.[1] estimate an average of 733 kg CO_2e/m^2 for commercial buildings in China.

These findings suggest the potential for reducing embodied carbon in Australia's commercial building sector. Targeted mitigation strategies, including increased use of recycled steel, engineered timber, and alternative cementitious materials, can play a critical role in lowering the sector's carbon footprint while supporting the transition to more sustainable construction practices.[8,39]

The estimated embodied carbon in Australian industrial buildings (262 kg CO_2e/m^2) closely aligns with the international average (264 kg CO_2e/m^2). In Australia, industrial buildings typically employ less material-intensive construction methods, such as steel-framed designs with reduced reliance on concrete. However, their extensive use of metallic materials results in higher average embodied emissions compared with residential buildings.

These cross-study comparisons should be interpreted with caution, as the benchmark values in Figure 6 are derived from studies that may differ in key methodological assumptions, such as building archetypes and LCA databases used for impact coefficients. While this makes direct global comparisons challenging, our estimates align well with previous Australia-specific analysis. This consistency across local studies provides a robust validation of our findings and suggests a distinct carbon footprint for Australian construction, differentiating it from the extremes often reported in international benchmarks.

Establishing this national baseline is a critical first step. However, designing effective mitigation strategies requires moving beyond national averages to understand how this environmental burden is distributed across the landscape. The spatial configuration of the built environment and the trade-offs between urban forms are primary determinants of this footprint and thus a key consideration for climate policy.

Expanded environmental footprint of construction materials

This study expands the scope of environmental impact assessments beyond carbon-centric approaches to encompass multiple sustainability dimensions, including resource depletion, air pollution, and toxicity. While embodied carbon remains a key metric, our findings demonstrate that focusing exclusively on carbon emissions overlooks other critical environmental burdens. For example, Australia's building stock embodies 1.2 billion metric tons of CO_2e, 8.34 billion cubic meters of water, and significant contributions to eutrophication, acidification, and air pollution—impacts that are often underrepresented in mainstream construction debates but are increasingly relevant to global sustainability targets.[40,41]

Key construction materials disproportionately drive these environmental impacts. Steel, for instance, is the dominant contributor to human toxicity impacts due to emissions from its energy-intensive production, while ceramics account for the highest level of fossil fuel depletion and particulate matter emissions. Although concrete is the most widely used material, its per-unit impacts are moderate; however, its substantial amount results in significant total environmental burdens. These findings align with global evidence highlighting that improving production efficiencies, increasing material reuse, and transitioning to renewable energy sources within material supply chains are essential strategies for reducing environmental impacts.[42]

When contextualized within global resource use patterns, Australia's per capita material intensity of 115 metric tons of embodied materials and 42.5 metric tons of CO_2e highlights the resource demands associated with its predominantly low-density urban form. By contrast, densely populated regions such as those in Asia and Europe tend to exhibit lower per capita material intensity but higher environmental impacts per GFA, particularly in high-rise developments.[37] This result suggests a need for tailored urban development strategies. For instance, in dense urban areas, policies could promote material circularity, such as incentivizing the use of recycled steel in high-rise buildings. In low-density suburbs, the focus could instead be on enhancing spatial efficiency through infill development and retrofitting, coupled with the use of low-carbon, locally sourced materials to reduce the total material and transport footprint.[7]

As operational emissions decline due to evolving construction standards and the ongoing transition to renewable energy, greater attention is shifting toward the embodied impacts of materials. This study identifies significant disparities across building typologies, with high-rise apartments disproportionately contributing to greenhouse gas emissions while SHs exhibit elevated freshwater ecotoxicity. These differentiated environmental impacts highlight the need for more integrated assessment tools that account for environmental performance indicators beyond energy or water use. Leading green building standards, for instance, are evolving beyond operational energy to incorporate the holistic, life cycle perspective that our study highlights. Rating systems like the Leadership in Energy and Environmental Design (LEED) in the United States[43,44] and the Building Research Establishment Environmental Assessment Method (BREEAM)[44] in the United Kingdom now feature credits that encourage whole-building LCA to address embodied carbon. These frameworks are increasingly health-focused, promoting material transparency and the avoidance of chemicals of concern to reduce toxicological risks. Similarly, Singapore's Green Mark scheme and Australia's Green Star rating tool embed life cycle considerations for energy, water, and indoor environmental quality into design and construction practices.[45,46] The expansion and strengthening of such integrated certification schemes are crucial for steering the construction sector toward sustainable development that protects both planetary and human health. Achieving this transition requires not only technological and financial interventions but also cultural and structural shifts that reshape material choices and design practices.[41,47]

Urban mining and circular economy strategies offer transformative potential for reducing the environmental footprint of Australia's construction sector. By recovering materials from demolished buildings, these approaches not only diminish the need for new production—critical for materials like steel, where production-stage processes (A1–A3) account for most global warming impacts—but also shorten supply chains, thus lowering transportation-related impacts (A4) for mass-intensive inputs such as sand and stone. SHs present significant recovery potential due to their large contribution to Australia's building stock. However, their dispersed nature poses a challenge to efficient collection. High-rise buildings with a higher material intensity offer more concentrated sources for urban mining. Policy initiatives like the circular design guidelines for the built environment in New South Wales, Australia, indicate growing adoption of these practices.[48] However, the operationalization of such practices requires precise, geolocated information on material age, state, and building location to reduce value loss during demolition.[49] A digital twin of building materials like the one constructed in this analysis could help bridge data gaps to help cities transition from reactive construction waste management to proactive mining,[50] reducing embodied carbon and reshaping construction processes toward circularity. Moreover, repositories for these used construction materials will be needed.[51]

Spatially differentiated strategies for sustainable urban growth

Our analysis evidences the distinct environmental impact profiles of different urban forms, showing that a "one-size-fits-all" approach to decarbonizing the built environment is inefficient (Figure 5). To be effective, mitigation strategies must be tailored to address the unique material drivers of each development pattern, from low-density suburbs to high-density urban cores.

The primary challenge for suburban areas is one of scale and volume. As the most predominant building type, SHs are the dominant driver of most impacts, requiring significantly more land. This extensive land footprint drives urban sprawl, contributes to habitat loss, and increases infrastructure demands.[52] Consequently, policies must focus on reducing the demand for new, low-density construction by incentivizing infill development and retrofitting existing stock over greenfield expansion. For new suburban construction, strategies should promote the use of low-carbon materials, such as certified sustainable timber and recycled aggregates, to decrease the overall material and carbon footprint.[34]

By contrast, the challenge for high-density urban and industrial zones is one of intensity and toxicity. While offering substantial land-saving benefits, these areas are hotspots for specific impacts due to their reliance on energy-intensive materials like steel and reinforced concrete.[53] Our findings show a concentration of mineral resource depletion in urban cores (33% of the national total) and human toxicity in industrial zones (23%). Effective strategies must therefore focus on material circularity and innovative design. This includes establishing robust markets for urban mining[54] and promoting approaches such as prefabricated modular construction, lightweight structural materials, and circular design principles that facilitate disassembly and material reuse.[42,55]

Ultimately, balancing the trade-offs between density, resource efficiency, and livability requires integrated planning that optimizes urban form while reducing environmental and social costs.[56] This balance is particularly critical for cities in the Global South facing rapid growth and limited resources, where choices between vertical and horizontal expansion are highly consequential.[53,57] By differentiating policy based on spatial form and prioritizing resource-efficient construction, cities can enhance livability, resilience, and sustainability within the limits of the Earth's ecological systems.

Limitations and uncertainties

The findings of this study should be considered in light of the inherent uncertainties associated with any national-scale model. Our analysis relies on a series of assumptions and aggregations

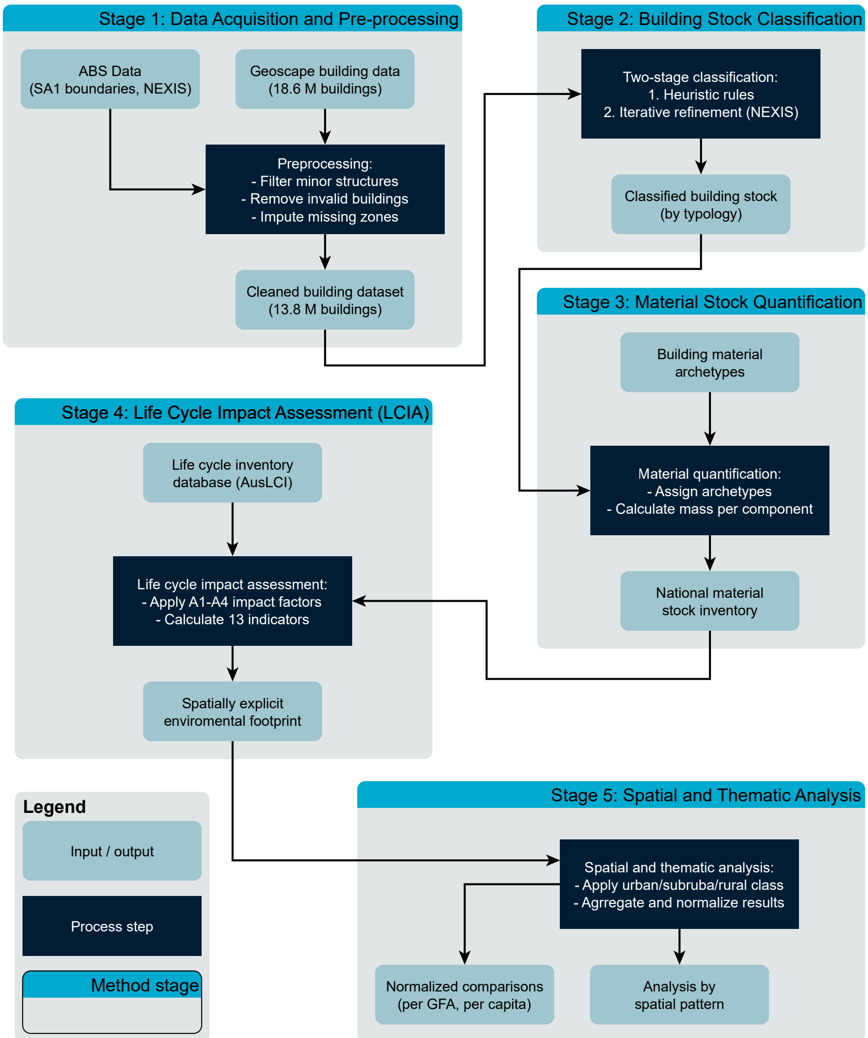

Figure 7. Analytical framework for quantifying material stocks and environmental impacts

to manage the complexity of the real world, where every building and city has unique characteristics. The primary sources of uncertainty stem from the building stock classification, the material intensity archetypes, and the life cycle impact assessment (LCIA) data.

To account for the heterogeneity of construction practices across different areas, our model does not apply a single national average. Instead, our methodology accounts for regional variations by weighting material archetypes according to the prevalence of pre- and post-1981 construction in each local SA1 census area, moving beyond a simple linear calculation. However, while our two-stage classification process was validated and refined using official Australian National Exposure Information System (NEXIS) data, uncertainty remains in the precise categorization of every individual building. Misclassifications, particularly between similar typologies like large SHs and townhouses, can influence the final distribution of materials. Similarly, the material quantification is based on archetypes representing typical construction practices. Although we used established, peer-reviewed Australian archetypes,[58] these cannot capture the full custom variability of the building stock.[59] The impact of this limitation is likely minimized by nationally consistent construction standards and the concentration of the building stock in the temperate zones reflected in the archetypes.

Finally, all LCA data contain inherent uncertainty in their impact factors. To ensure consistency and minimize inter-database variability, we exclusively used the standardized Australian Life Cycle Assessment Society (ALCAS) best-practice database for Australia. It is important to note that our study focuses on embodied impacts (modules A1–A4) and does not include operational impacts (which are affected by factors like weather and occupant behavior) or end-of-life scenarios, which would require further assumptions about future technologies and policies. Despite these limitations, this study provides a robust, spatially explicit baseline that represents the most comprehensive assessment of Australia's building stock to date.

METHODS

The study was conducted for Australia, a geographically expansive but sparsely inhabited country.[60] We developed a comprehensive analytical framework to estimate the material stock and associated environmental burden of the national building portfolio, as illustrated in the methodological workflow (Figure 7). Our process comprises five main stages. The analysis begins with (1) data acquisition and pre-processing, where raw geospatial data for 18.6 million buildings is cleaned and prepared. This is followed by (2) a two-stage classification to assign a specific typology (e.g., SH and high-rise apartment) to each of the 13.76 million buildings in the final dataset. In the third stage, we perform (3) material stock quantification, assigning construction archetypes to each building to estimate the mass of 14 key materials. Subsequently, we conduct (4) a cradle-to-site LCIA to calculate 13 distinct environmental impact indicators and building area analysis to estimate the land footprint of building types. The final stage involves (5) spatial and thematic analysis, where we aggregate these impacts by different development patterns (urban, suburban, and rural) and normalize them by GFA and per capita. The following sections provide a detailed description of each stage, and a detailed explanation of some components is available in the supplemental information.

Building data collection and processing

We extracted volumetric building data from the Geoscape Building dataset (version 3.3),[61] which provides information on roof and eave heights, primary roof materials, and footprints for structures exceeding 9 m^2, a total of 18.6 million buildings. Using this dataset, we generated volumetric estimates for all Australian buildings. Geoscape classifies buildings based on planning zones, footprint size, and height. To refine our dataset, we excluded sheds and minor constructions by discarding buildings with a footprint smaller than 40 m^2 and removing structures within water bodies. This filtering process eliminated 26% of the buildings in the original dataset but only 3.2% of the total footprint area built, ensuring that minor structures did not disproportionately influence the analysis. For the remaining 13.76 million buildings with missing planning zone information (1.23% of the dataset), we applied a sliding majority approach, assigning zoning classifications based on the most common zoning type among their 20 nearest neighboring buildings.

Building classification

Stage 1: Parameter-based classification

The Geoscape dataset does not include explicit information on building types (e.g., SHs or apartment buildings). To address this, we developed a classification framework based on conditional logic, incorporating land-use zoning, height thresholds, and footprint area. Details of these classification parameters are provided in the supplemental information. Using this approach, we categorized buildings into six primary types: SHs, 1–2 story apartment buildings, 3-story apartment buildings, 4+ story apartment buildings, commercial buildings, and all other buildings (including industrial and public buildings).

Validation of parameter-based classification

To assess the accuracy of this classification procedure, we compared the results against a manually corrected dataset comprising 159,311 buildings in the Australian Capital Territory.[6] This approach achieved high precision and recall (over 99%) for industrial and commercial buildings, demonstrating strong performance in distinguishing these typologies. However, classification accuracy was lower for SHs and high-rise apartment buildings (cf. Table S5, stage 1). Misclassifications were particularly prevalent between SHs and low-rise apartments (F12), necessitating further refinement.

Stage 2: Reclassification using NEXIS data

To improve the initial classification, we implemented a reclassification algorithm using regional and state-level target proportions of building types sourced from the NEXIS version 15.[29]

The reclassification process was iteratively refined to align building type shares with the official NEXIS data using mean absolute error (MAE), root mean squared error (RMSE), and percentage difference as evaluation metrics.

Key features of the reclassification algorithm were as follows:

- rule-based assignments: restrictions ensured that buildings could only transition between plausible classifications (e.g., buildings in commercial zones could not be reassigned to residential categories);
- weighted adjustments: underrepresented classes from stage 1 were given higher reassignment weights to improve balance;
- locking mechanism: to prevent infinite loops, buildings were temporarily locked from immediate reclassification after reassignment; and
- convergence criteria: the reclassification process terminated when discrepancies fell below a predefined threshold or when no reassignments occurred for five consecutive iterations.

Validation of reclassification using NEXIS data

At the national level, the estimated shares of industrial buildings, 3-story apartment buildings, and 4+ story apartment buildings closely matched the reported NEXIS distributions. The share of SHs determined in stage 2 (90.6%) more closely approximated the reported NEXIS share (85.6%), indicating a substantial improvement over the initial classification (Table S5).

However, the share of 1–2 story apartment buildings remained underrepresented by 6%. This discrepancy is likely due to townhouses, which were more frequently assigned to the SH category rather than the low-rise apartment category.

Overall, the two-stage reclassification process significantly improved the alignment between model estimates and reported building distributions. By adjusting for overrepresented categories, the refined classification yielded a more realistic representation of building typologies across Australia. Figure 8 shows an example of the 3D building polygons and classes used in our analysis.

Spatial classification of development patterns

To analyze the environmental impacts of different spatial forms, we applied a hybrid classification to categorize each building as urban, suburban, industrial, or rural. Standard administrative boundaries were found to be too coarse for this purpose. Our approach, therefore, used a hierarchical, rule-based method that combines official land-use planning zones with building typology data, which serves as a direct proxy for land-use intensity and density.

For each building i, with a planning zone z_i and a building typology t_i, we assigned a spatial class, S_i, based on the following hierarchical rules:

$$S_i = \begin{cases} Urban\ if\ (z_i \in Z_{Urban}) \vee (t_i \in T_{Suburban}) \\ Rural\ if\ (z_i \in Z_{Rural}) \\ Suburban\ if\ (z_i \in Z_{Suburban}) \wedge (t_i \in T_{Suburban}) \\ Industrial\ if\ (z_i \in Z_{Industrial}) \vee (t_i \in T_{Industrial}) \end{cases}$$

Where the sets of planning zones were defined as

$$Z_{Urban} = \{Commercial, Business, Mixed\ Use\}$$

$$Z_{Rural} = \{Rural\ or\ primary\ production, Conservation, National\ Parks\}$$

$$Z_{Suburban} = \{Residential, Special\ Use, Community\ Use, Recreational\ and\ Open\ Spaces\}$$

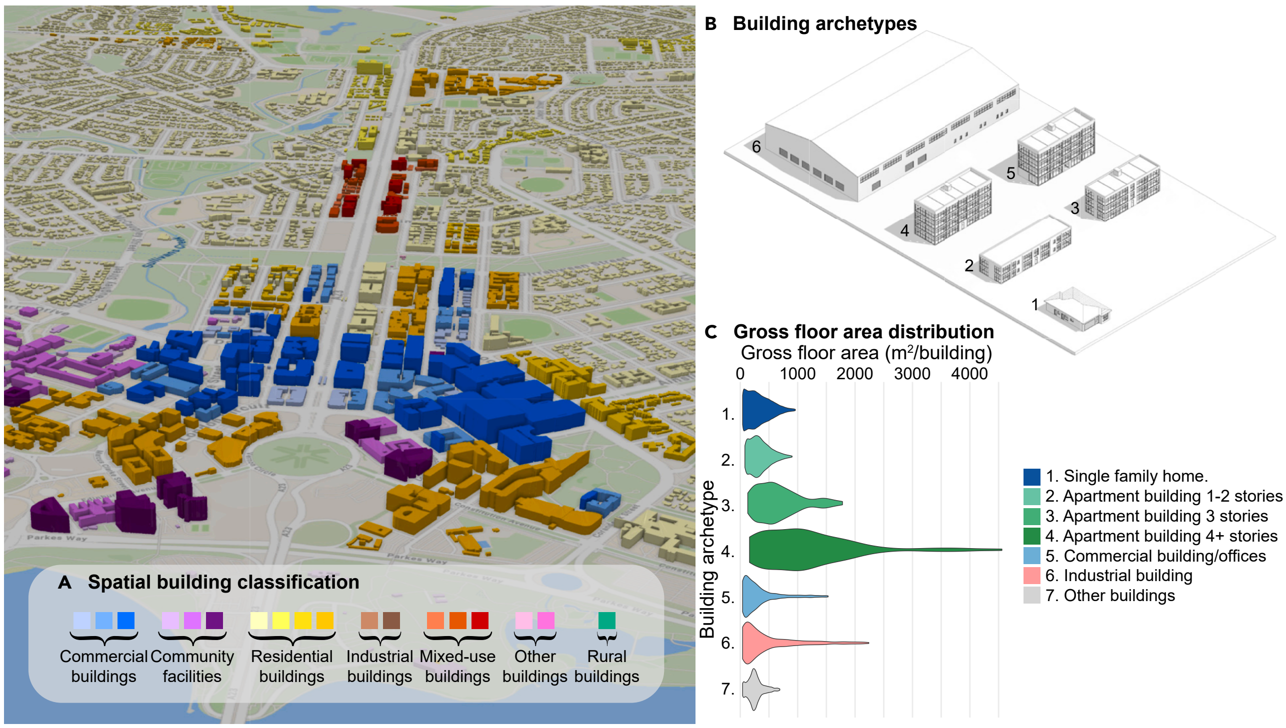

Figure 8. Building classes by main typology

(A) Example of 3D buildings and classification by number of stories (color gradient with darker colors indicating taller buildings).

(B) Representation of main building archetypes used in our study.

(C) GFA distribution.

$$Z_{Industrial} = \{Industrial, Utilities, Transport\ Infrastructure\}$$

And the sets of building typologies were defined as

$$T_{Urban} = \{F4, F47, M47, \text{M835}, \text{C47}, \text{C835}, \text{CF47}, \text{CF835}, \text{OTH47}, \text{OTH835}\} \text{ high-rise archetypes}$$

$$T_{Suburban} = \{SH, F12, F3\} \text{ low-rise archetypes}$$

$$T_{Industrial} = \{I1, I2\}$$

The classification was applied sequentially, following the hierarchy in the formula.

Quantification of embodied materials according to construction periods

We integrated polygonal information from 3D building envelopes and building classes with building archetypes categorized by construction period and typology (e.g., single houses, apartments, commercial, and industrial buildings) from Stephan and Athanassiadis.[22] Archetypes were merged with material assembly datasets to account for each building's unique assembly attributes (e.g., window-to-wall ratio, material-specific quantities, and lifespan) in the estimation of embodied materials. The number of stories n, for building i of class b was estimated using roof height h_{roof} and characteristic height thresholds for building type b, h_b using the formula:

$$n_{i,b} = \begin{cases} 1, if\ h_{roof,i} \leq h_b \\ round\left(\dfrac{h_{roof,i}}{h_b}\right), otherwise \end{cases}$$

Usable floor area (UFA) was computed as $UFA_{i,b} = 0.9 * A_{i,b} * n_{i,b}$, where $A_{i,b}$ is the ground floor area. The outer wall assembly area (AOW) was estimated as $AOW_{i,b} = (1 - WFR_b) * P_i * h_{eve,i}$ with window frame ratio (WFR) representing a window-to-wall ratio coefficient specific to building type b, P_i is the perimeter of building i, and $h_{eve,i}$ is the eave height of building i.

Other building components, including columns and beams, doors, roofs, piping, wiring, internal walls, carpets, paint, and minor finishes, were estimated from the building area and height characteristics, reflecting conventional design practices and empirical estimates from previous studies.[5,6,22] The mass of material in each building component (e.g., metric tons of timber in single house walls) was then estimated using factors (e.g., metric tons per cubic meter of timber) derived from prior work and industry standards.[5,6,22] It is important to note that the "sand and stone" category quantifies unbound aggregates used for site preparation, foundations, and fill. This is separate from and exclusive of the sand and gravel aggregates that are already included as components of the "concrete" material category to prevent double-counting. Table S8 lists the fourteen materials that were included in our analysis.

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To ensure computational efficiency and scalability, a parallel processing routine was implemented but still required around 4 days of computing time in a Windows 11 Enterprise system with 128 GB of random access memory and 12 cores. This routine iterated over each building type and its associated functional units, aggregating the computed material quantities and converting them into metric tons. The final outputs were then organized into datasets for each building typology and for two construction periods before and after 1981, which was a year of substantial changes in construction regulations in Australia.[29] More specifically, we used construction typologies associated with the periods 1971–1980 and 2001–2007.

EEI estimation

For each building i and construction period t, the EEI j of material m in building assembly a was multiplied by the metric tons of material m estimated in each assembly for period t,

$$Impact_{i,m,a,t} = tonnes_{i,m,a,t} * EEI_{j,m,a}$$

Where t indicates construction technologies for one of the periods 1971–1980 or 2001–2007 for each building typology. The assemblies accounted for are listed in Table S8, and the assessed EEIs are described in Table S9. LCA is a useful method for environmental assessments in the building sector, allowing the quantification of environmental burdens across various life cycle stages.[62,63] In Europe, standards such as European Norm (EN) 15978 ("assessment of environmental performance of buildings")[64] and EN 15804 (core rules for environmental product declarations)[65] further guide the evaluation of construction sustainability. Figure S1 illustrates the general life cycle stages of a building according to EN 15978. Our study applies this framework to the "cradle-to-site" stages, which include raw material supply (A1), transport to the manufacturer (A2), manufacturing (A3), and transport to the construction site (A4). This scope was selected to estimate the upfront embodied impacts of Australia's building stock. The midpoint approach used in the ALCAS Best Practice LCIA Carbon Neutral V2.05 method[66] was selected for stages A1–A3 to ensure consistency across various impact categories. This approach, which calculates impacts based on midpoint indicators, offers more reliable comparisons between individual categories than endpoint (damage-oriented) or single-score assessments.[67]

Environmental impact on product stage (A1–A3)

The integration of environmental and material footprint estimates for buildings constructed during 1971–1980 and 2001–2007 was informed by data from the NEXIS.[29] This dataset provides spatially explicit estimates of the proportion of buildings within each SA1 region that were built before and after 1981. SA1 regions, the smallest unit of census data aggregation, have an average population of approximately 400 people, with 57,523 SA1s distributed across Australia.[68]

Given the lack of individual building age data, we approximated the material and environmental footprint of each building as a weighted combination of construction period-specific estimates, proportional to the prevalence of pre- and post-1981 buildings in its corresponding SA1. For instance, if a given SA1 contains X% of building type b constructed before 1981 and $(1 - X)$% built thereafter, the material and environmental footprint for each commercial building (i) in that SA1 is estimated as

$$E_{i,b,stock} = \left(X * E_{i,b,1971-1980}\right) + \left([1 - X] * E_{i,b,2001-2007}\right)$$

where $E_{i,b,1971-1980}$ and $E_{i,b,2001-2007}$ indicate the environmental and material footprint estimates based on the construction technologies of each period. This approach accounts for regional variations in the building stock age.

Environmental impact on transportation (stage A4)

Environmental impacts from transporting construction materials from their manufacturing source to Australian construction sites (stage A4) were estimated according to their country of origin. Table S10 indicates the transportation parameters, including average land and sea distances, for the analyzed materials. For instance, materials such as cement, steel, and ceramics are associated with shipping and on-road distances based on country-of-origin information. To quantify these impacts, the Transport Network Strategic Investment Tool (TraNSIT) Web tool[69] was used to determine average trip distances for each material type. Materials originating overseas were weighted according to their respective ports of origin, using trade data sourced from United Nation's Comtrade,[70] the Australian Steel[71] and the Cement Industry Federations,[72] and OXEN logistics.[73] Port-to-port distances were estimated for shipments arriving in Australia, and these distances were then combined with transport intensity factors for both transoceanic freight shipping and heavy-duty road transport (lorry > 32t) as provided by the Australian National Life Cycle Inventory database.[74] The environmental impact for the estimated metric tons of material, m, embodied in buildings in 2023 for each transport mode was calculated as

$$Impact_m = Distance\_km_m * Transport\ intensity\ factor$$

Land footprint

The estimation of the total and average land footprint for building types does not rely on LCA. The total land footprint of each building class was calculated by summing the area of each individual building's footprint polygon as provided by the high-resolution Geoscape dataset. This bottom-up aggregation provides a precise measure of the land area directly occupied by the building stock, a key indicator for assessing urban sprawl.

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Raymundo Marcos-Martinez (raymundo.marcosmartinez@csiro.au).

Materials availability

This study did not generate new, unique materials.

Data and code availability

Access to the building footprint data used in our analysis requires a license from Geoscape Australia (https://geoscape.com.au/solutions/built-environment/). The code used in this analysis will be made available upon reasonable request by the lead contact.

Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

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AUTHOR CONTRIBUTIONS

R.M.M., A.M., N.S., N.E., and H.S. contributed to the project conceptualization, visualization, and writing of the original manuscript draft. R.M.M. led data curation and formal analysis with support from N.S., N.E., and A.M. Y.F. supported the visualization component. S.W. acquired the funding for this research. All authors contributed to the review and editing of the final manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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