BUILDING MATERIALS AND THE CLIMATE: CONSTRUCTING A NEW FUTURE

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Global Alliance for Buildings and Construction

Yale

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ABBREVIATIONS

°C	Degrees Celsius
ASEAN	Association of Southeast Asian Nations
BPIE	Buildings Performance Institute Europe
BREEAM	Building Research Establishment Environmental Assessment Methodology
CCS	Carbon capture and storage
CO_2	Carbon dioxide
EJ	Exajoule
EPD	Environmental Product Declaration
EU	European Union
G7	Group of Seven
GDP	Gross domestic product
GlobalABC	Global Alliance for Buildings and Construction
Gt	Gigaton
HFC	Hydrofluorocarbon
IEA	International Energy Agency
ISO	International Organization for Standardization
kW	Kilowatt-hour
LEED	Leadership in Energy and Environmental Design
m2	Square metre
NDC	Nationally Determined Contribution
OECD	Organisation for Economic Co-Operation and Development
PEEB	Programme for Energy Efficiency In Buildings
PV	Photovoltaic
SDG	Sustainable Development Goal
SDS	Sustainable Development Scenario
TWh	Terawatt-hour
UN	United Nations
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
W	Watt

KEY TERMS

Buildings and construction: All of the activities that encompass the making of buildings, including the construction of both residential and commercial buildings. The five primary sectors of the construction industry are residential, commercial, heavy civil, industrial and environmental construction.

Built environment sector: All of the activities that encompass the making of environments for human occupants and activities, including the construction of homes, commercial buildings, streets, highways, infrastructure and zoning.

Built environment process: All of the activities, processes, and decisions that encompass the making of environments for human occupants and activities, across the life cycle of building projects from extraction to design construction and end of life, including the construction of homes, commercial buildings, streets, highways, infrastructure and zoning.

Carbon dioxide equivalent: An equal green-house gas emissions quantity that represents the number of metric tons of (CO_2) emissions with the equivalent global warming potential as another greenhouse gas. It is commonly used, since it is the primary component in greenhouse gas emissions that result from the use of fossil-based energy and emissions from biological materials, waste and chemical reactions.

Carbon capture and storage: In the context of buildings and construction, carbon capture refers to active processes of removing carbon from the atmosphere through processes such as plant photosynthesis and carbonation in cementitious materials. Carbon storage refers to how carbon is kept within the building material itself over time.

Carbon loophole: The greenhouse gas loophole that is created by global trade, whereby production of materials are relocated and emissions allocated to contexts with lower production costs and historic emission patterns.

Carbon offsets: Instruments that allow companies to demonstrate net zero greenhouse gas emissions by paying for an activity outside of its organization that verifiably reduces greenhouse gas emissions. They are measured in units of one metric ton of CO_2-equivalent emissions, and they have an "additionality" requirement, which means that they must come from a process that is verified to be "additional" to what would happen under typical "business-as-usual" scenarios.

Circular economy: An economy that uses a systems-based approach in order to maintain the lifespan and/or circulation of materials, products, and services for as long as possible. "Circularity" is a common term that refers to production processes and economic models that are restorative and regenerative, enabling resources to maintain their highest value, firstly by "avoiding" their extraction in the first place through "improving" design processes to eliminate waste and material overconsumption, and secondly by "shifting" to renewable and recycled materials (U.S. Environmental Protection Agency 2023).

Design for Freedom: A movement and initiative by Grace Farms to create a radical paradigm shift within the built environment towards ethically sourced, forced labour-free materials.

Embodied carbon: A term commonly used in the built environment industries to denote the amount of CO_2 that is emitted as a result of all the energy that goes into a material's production (extraction, manufacture) construction, maintenance, refurbishment and end-of-use (demolition, incineration, landfill, etc.) across the life cycle of the built environment process.

Environmental product declaration (EPD): A document that is meant to transparently communicate the environmental performance/impact of a product or material across its life cycle.

Forced labour: All work or service that is extracted from any person under the threat of a penalty and for which the person has not offered themself voluntarily.

Greenhouse Gas (GHG) Protocol: A framework established by the World Resources Institute and the World Business Council for Sustainable Development to assist stakeholders across the built environment process such as governments, businesses, industry associations, non-go-vernmental organizations and other entities, to identify, measure, manage and report the greenhouse gas emissions that result from their activities, according to standard guidelines.

Life-cycle assessment: A procedure for tabulating and reporting the environmental impact of a material, product or service over its lifetime. The life-cycle assessment process includes the following procedures: 1) goal and scope definition, 2) inventory analysis, 3) impact assessment and 4) interpretation.

Operational carbon: Emissions generated through the function and maintenance of the building.

Scope 1, 2 and 3 emissions: The GHG Protocol classifies greenhouse gas emissions into three different scopes: Scope 1 emissions are direct emissions that occur from a source that can be controlled by an organization. Scope 2 emissions refer to indirect emissions that result from the generation of purchased energy. Scope 3 emissions are indirect emissions that occur in the value chain of the reporting entity (company, municipality, community, etc.) including both upstream and downstream emissions, but that are not in the control of the reporting entity.

Whole life-cycle assessment: A method that quantifies the carbon impact of a material or process across the entire building life cycle, from embodied to operational carbon and end of use. Whole life-cycle assessment requires rigorous standardised methodology so that the scope and benchmarks of assessments can be transparently communicated and evaluated.

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BUILDING MATERIALS AND THE CLIMATE

Executive Summary

Building Materials Are Set to Dominate Climate Change

Urbanisation is rising and policy action is urgently needed to shift building material life cycles towards regenerative methods.

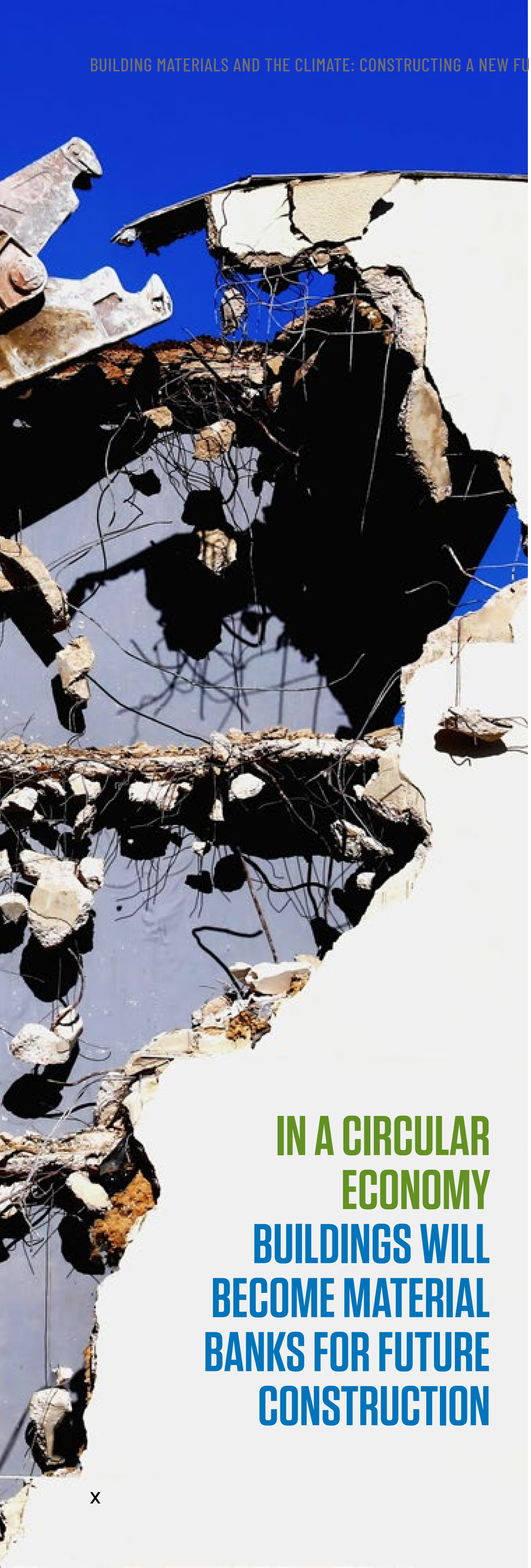
The built environment sector is by far the largest emitter of greenhouse gases, responsible for at least 37 per cent of the global emissions. Yet it has received only a small fraction of climate-focused development funding, compared to other sectors. Until now, most of the progress in the sector has been made on reducing the "operational carbon" of a building – the emissions created from heating, cooling and lighting, which are projected to decrease from 75 per cent to 50 per cent of the sector in the next few decades. However, solutions for reducing the "embodied" carbon emissions from the design, production and deployment of building materials such as cement, steel, and aluminium have lagged far behind. The reasons for this are complex and many actors are involved. Therefore, the incentives for decarbonisation need to simultaneously enable decision makers, from producers to consumers across the global material supply chains, in both informal and formal building sectors. This report highlights the urgent need to develop new models for cooperation on the decarbonisation of building materials, if the world is to reach its goals for net zero emissions from the built environment sector by the mid-century.

The report focuses on three urgent pathways that must be facilitated by supporting stakeholders across the lifecycle of the built environment sector in order to decarbonise:

AVOID the extraction and production of raw materials by galvanising a circular economy, which requires building with less materials through better data-driven design, while reusing buildings and recycled materials wherever feasible.

SHIFT to *regenerative* material practices wherever possible by using ethically-produced low carbon earth- and bio-based building materials (such as sustainably sourced bricks, timber, bamboo, agricultural and forest detritus) whenever possible.

IMPROVE methods to radically decarbonise conventional materials such as concrete, steel and aluminium, and only use these non-renewable, carbon-intensive, extractive materials when absolutely necessary.



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IN A CIRCULAR ECONOMY BUILDINGS WILL BECOME MATERIAL BANKS FOR FUTURE CONSTRUCTION

Reducing embodied carbon in building materials to net zero is achievable by 2060, if we promote the development and use of best available technologies for decarbonising conventional materials, combined with a major push to advance the increased use of regenerative, circular biomaterials from forest and agriculture streams. One of the most important opportunities for synergistic potential to decarbonise the sector lies with the ability to link the production of building materials with the management of carbon cycles of forests and agricultural lands. This would produce compounding benefits, from reducing the risk of forest fires, to increasing the productivity of forested and agricultural land tracks through rejuvenation and responsible reforestation. Increased investment is needed to redirect global biomass residues into cost competitive construction products such as cementitious binders, bricks, panels and structural components. Compounding benefits include the capacity to store carbon within building materials and products, thereby reducing climate change emissions from decaying matter, forest fires and the burning of crop waste. Further, major carbon sequestration benefits could come from new cooperative approaches between builders and forest managers to increase the biodiversity of forests through the selection of functional attributes for building materials according to species.

Policies to support material producers and users across the building life cycle range from land-use management to carbon certifications. However, the effects of material selection on ecosystems need to be better incorporated into assessments. Global co-operation is critical towards ensuring a just transition to ethical decarbonisation. Stakeholders in the building process must have access to reliable data on the provenance of materials to ensure that carbon taxes and other regulations are not greenwashing material products that have been made with unfair labour, or are detrimental to local biodiversity and the life quality and expectancy of regional populations.

Across different regions and climates, methods will vary in implementing the three main decarbonisation principles discussed in this report: "Avoiding" emissions through circularity, "Shifting" to sustainable materials, and "Improving" the production of extractive materials. Patterns in global material flow scenarios point towards two key differences: in developed countries, the focus will be on renovation of the existing and ageing building stock, whereas in developing countries, the need for new construction is evident in the face of rapid urbanisation.

THREE PRINCIPLES FOR ENACTING MATERIAL DECARBONISATION

1. AVOID Waste, Build (with) Less and Improve Circularity

There are opportunities for circular design, recycling and re-use at each phase of the building life cycle.

The potential to reduce and avoid embodied carbon is greatest during the planning and design phases, reinforcing the importance of taking a whole building life-cycle approach in circular economy design. In a circular economy, where waste is eliminated, extending a building's life is the most valuable and least-wasteful option – with renovation generating 50-75 per cent fewer emissions than new construction. New construction can incorporate circular design strategies – promoting "design for disassembly" – that result in at least 10-50 per cent decrease in greenhouse gas emissions. Early design choices greatly impact the ability to reuse or recycle materials later in the building cycle.

Transitioning to a circular economy is one of the essential paths towards reducing carbon emissions in buildings. Critically, it requires rethinking how buildings are designed. Design decision-making during each phase of a building's life cycle offers opportunities to reduce embodied carbon. Informal construction sectors tend to already excel at a circularity and reuse, however in formal sectors, key circular economy design strategies include computer-aided design optimisation for less material usage, selecting materials that reduce non-renewable material extraction, designing for material and component reuse, and extending the life of buildings and/or materials through proper maintenance.

Despite growing awareness, most contemporary material cycles continue to be more linear than circular. As a result, non-renewable, energy-intensive materials still supply the majority of demand. So far, recycled materials are not available in sufficient quantities and qualities, and the gap between supply and demand for recyclables is growing in most sectors. A new supply-and-demand model is needed, with new enterprises that allow for the careful dismantling of buildings and for the storing, preparation and maintenance of second-cycle materials for resale that will enable circular economies while providing job opportunities.

Facilitating access to reliable information and verification is key. Decision-makers must support efforts by stakeholders across the building industry as they seek to decarbonise materials. The current fragmentation of the industry is undermining decarbonisation efforts – with insufficient cooperation among manufacturers, architects, engineers, builders and recyclers. Efforts by individual stakeholders to improve decarbonisation outcomes will not succeed unless they are supported by policy and finance across the different phases of the building process. For example, efforts by designers and communities to use more recycled materials are often stymied by the growing gap between supply and demand. Yet this gap cannot be closed without the adoption of building codes that require designers to specify "circular" components made with re-usable, renewable materials. Even small improvements to synergistically support both producers and users through policy and finance would be preferable to isolated actions.

Avoid New Extraction by Enabling a Circular Material Economy That Prioritises Reuse and Recycling

In developed economies, it is critical to improve industry methods across stakeholders, from designers, to communities and to commit to repurposing the massive quantities of failing reinforced concrete from 20th-century infrastructure that is nearing the end of its first life, so that it can be transformed into material "banks" for new construction to slow the pace of non-renewable material extraction. To do so, far more investment is required for research and development of design and secondary manufacturing methods with equipment to recover and process construction, renovation and demolition materials.

Government incentives, awareness campaigns, and legal and regulatory frameworks have shown to be effective to incentivise approaches for re-use and recycling. Recycling systems for building materials tend to require similar kinds of support across countries, including promoting markets for re-usable products, providing incentives for the creation of re-use centres and developing specialised contractors. Due to the interdependent nature of the built environment sector, in which many materials may be used across building systems and types, far more investment is required for measures that ensure cooperation across sectors and borders.

Shuto Morioka / EyeEm Collection via Getty Images

NEW COOPERATIVE MODELS BETWEEN THE BUILDING, FORESTRY, AND AGRICULTURAL INDUSTRIES COULD LEAD TO A REVOLUTION IN THE CARBON CYCLE MANAGEMENT OF REGIONAL ECOYSTEMS

2. SHIFT to Bio-Based Building Materials

Innovating beyond business-as-usual forestry: materials that are truly renewable require regenerative approaches to resource management that incentivize biodiversity.

In pursuing the second pathway to decarbonisation, there are transformative opportunities to develop ecologically sound methods for managing the carbon cycle of regional forests and agricultural lands, with important co-benefits to consider, as well as risks. Bio-based materials may represent our best hope for radical decarbonisation through the responsible management of carbon cycles. The shift towards properly managed bio-based materials could lead to compounded emission savings in the sector of up to 40 per cent by 2060 in many regions, even when compared to savings from low-carbon concrete and steel.

However, envisioning and implementing a large-scale transition to circular and bio-based materials in the built environment carries substantial risks if the changes to the broader ecological, social and economic context are not planned for and handled very carefully. Decarbonisation of buildings creates risks of unintended consequences to the ecosystems that underpin the production to supply the alternative bio-based materials. It can also lead to the perpetuation or exacerbation of unjust labour practices, and to inequitable shifts in economic gains and losses as industries transition.

Renewable, bio-based building materials have a unique capacity to drive reductions in atmospheric carbon, if they are sustainably sourced and managed. Currently, wood is the leading scalable biomaterial, and patterns of timber production and use offer both opportunities and challenges. The rising demand for timber could accelerate markets for upcycling by-products from forests and agriculture, adding the massive potential benefits of reducing forest fires and greatly expanding the carbon sequestration potential of both forests and urban areas by up to 70 per cent in certain regions. However, a key prerequisite is that intersectoral approaches to renewable resource and land management are urgently required to transition away from the high carbon impacts of much "business-as-usual" forestry and agriculture.
Key recommendations for bio-based materials include standardisation of performance, integration into building codes, broad industry upskilling, marketing and financial incentivisation, and regulated cooperation in sustainable land-use techniques:

1. **Mandate the Use of Living Systems and Biomass to Protect Urban Climates**

Perhaps the most impactful policy for changing the impact of urban materials on climate change is to mandate the use of vegetated surfaces to cover a percentage of exposed concrete or asphalt, wherever possible. This has the combined impact of naturally keeping buildings cool, reducing energy consumption, as well as absorbing storm water to reduce flooding, replenish water tables and urban biodiversity.

2. **Promote the Transition to Low-Carbon Materials**
Decarbonisation of the cement sector and other major emitters is being enhanced by replacing traditional methods with hybrid bio-based materials and other low-carbon materials. However, these emerging methods are not yet cost competitive, and widespread biases remain that protect entrenched methods. Thus, scaling up requires substantial investment in research and development of both major and emerging producers, alongside incentives and/or enforceable building codes.

3. **Shift Public Perceptions regarding Traditional Vernacular Materials**
Why has it been so difficult to decarbonise building materials, and what can be done about it? People have not always built with carbon-intensive materials and their future use is not inevitable. Before the middle of the 20th century, the vast majority of cultures built large buildings and cities out of indigenous earthen, stone and bio-based materials – such as timber, cane, thatch and bamboo. However, during the last century, with ever greater access to fossil fuels, the global extraction and production of carbon-intensive, mineral-based materials (such as concrete and steel) exploded and became widely associated with the image of modern progress, strength and expediency.

Yet many contemporary building structures and materials only give the illusion of durability, as they were “designed for obsolescence”. Building assemblies with limited lifespans are now destined for landfills at demolition, as they have been procured through complex supply chains and are not designed for easy disassembly or re-use. An example is the vast number of failing concrete structures with steel and glass façades across the developed world that need to be replaced just a few decades after they were built. Meanwhile, stone, wood and even massive mud buildings have been maintained for centuries with their structures intact.

This report outlines key policies and tools that can be adopted by multiple stakeholders at different phases of the building process that look beyond operational energy and that facilitate the radical acceleration of building decarbonisation, while also bolstering the health of both human populations and biodiverse ecosystems.

4. **Harnessing technology to improve materials while recapturing the intelligence of the past**
Contemporary materials do not inherently lack durability. However, it is possible to achieve much better performance from contemporary materials and buildings by harnessing data and technology to revolutionise the means and methods of design and construction. To reach net zero emissions in the built environment sector, the building materials of the future will need to be procured from renewable or reusable sustainable sources wherever possible. If raw material extraction must take place, then dramatically improved methods for decarbonisation must be implemented by transitioning to renewable electrification of all processes, and complemented by carbon capture and storage methods that require substantial support for research and development in order to demonstrate scalability.

Timber and Wood

Future scale up of timber requires careful management of the carbon cycle of forests and agricultural lands in order to increase their net productivity for both carbon sequestration, food and material production.

The built environment uses 38 per cent of the world’s wood products. Increasingly, mass timber is becoming an attractive alternative to carbon-intensive concrete and steel due to its potential for scalability, sustainability, strength and flexibility in mid-rise urban buildings. Advances in timber building material technologies are making it possible to shift towards large-scale structural timber products, provided that the timber industries continue to innovate and are regulated for sustainable practices. Ensuring that the vast majority of timber is sourced from sustainable forestry will be crucial for making this a truly sustainable transition, avoiding pitfalls such as lax regulations, particularly in emerging economies. It is critical to prioritise the development of afforestation practices, particularly in natural forests of tropical countries, where logging rates far outpace effective replanting. “Circular timber” includes the increased use of forest by-products. Both clear-cuts (decaying logs and residues from logging) and off-cuts from wood manufacturing have potential for reconstituted wood products.

Bamboo

Scaling fast-growing bamboo shows major promise but requires innovation in carbon-neutral binders.

Bamboo is a fast-growing renewable resource that has witnessed significant advances as a scalable building material in the last two decades. Progress in engineered bamboo has demonstrated structural performance similar to that of cross-laminated timber and steel. However, the variability in species across regions requires investments in further development of low-cost and low-carbon construction methods, standards and certifications to gain the confidence of industry for large-scale applications. As with all engineered bio-based materials, incentives urgently need to prioritise progress in “green chemistry” to develop non-toxic binders and glues. As with timber, the sustainable scaling of the supply of bamboo is critical, with regulations in place that avoid clear-cutting of forests while gaining access to land, and also ensure transparency of sustainable practices throughout the supply chain.

Biomass

The recuperation of by-products from forestry and agriculture has synergistic benefits of reducing forest fires and crop burning.

Non-timber lignocellulosic materials generated from forestry, agriculture and biomass residues represent an untapped but potentially massive local supply chain for building materials, from sources that currently go to waste and contribute substantially to greenhouse gas emissions that also affect air, land and water quality across regions. However, major investments are required. If scaled up to reduce the use of petrochemical and/or timber-based building materials, fast-growing lignocellulosic materials could significantly lower the projected peak in global carbon dioxide emissions.

What is a whole life-cycle approach, and why is it critical for decarbonisation of the sector?

The report emphasises the need to take a whole-life cycle approach when assessing strategies to decarbonise emissions from the built environment. A whole life-cycle approach is radically different from a linear approach as it incorporates the principles of a circular economy. It requires consideration of the environmental impacts of material choices before the materials are even extracted, and then again at each phase of the building life cycle, from extraction to processing, installation, use and demolition. This means thinking about how the choice of materials impacts everything from the functioning of regional ecosystems, human health and wellbeing, to the amount of heating or cooling needed – and how, at the end of their use, these materials can provide a "bank" of resources to then be re-used.

When taking such an approach, the work of the geo-biosphere to produce specific local natural resources is valued as a renewable resource. Therefore, the use of bio-based and renewable materials such as timber, bamboo and biomass products must be supported with regulations to protect the ecosystems that sustain those resources, with careful consideration of regionally specific, sustainable land use and forest management.

Whole life-cycle thinking requires sensitivity to the context – to local cultures and climates. A shift to low carbon earth- and bio-based building materials is often technologically possible but socially difficult to implement, as many cultures consider concrete and steel to be "modern" materials of choice. Yet there is great potential to shift to low-carbon materials due to advances in engineered timber, bamboo and biomass as substitutes for steel and concrete.

3. IMPROVE Non-Renewable Building Materials and Processes

Supply of reused and recycled materials will need to catch up with growing demand.

For material producers, some of the highest-priority pathways to decarbonise are by improving the processing of conventional materials such as concrete, steel, aluminium, plastics, glass and bricks. Key to all efforts will be electrifying and decarbonising the energy that is used to produce and maintain materials, buildings and urban infrastructure across their life cycle. Most material economies continue to be predominantly linear, rather than circular. As a result, virgin and non-renewable materials, that are energy-intensive to produce, still provide the majority of today's material demand, while recyclables are not available in sufficient quantities and qualities. Reducing raw material extraction and harvesting through recycling and re-use may also mitigate social ills such as forced labour upstream in the supply chain.

Facilitate the Decarbonisation of Conventional Non-Renewable Materials

Cement, steel and aluminium are the three largest sources of embodied carbon in the building sector. The lowest hanging fruit is to facilitate and/or mandate the adoption by industry as well as energy infrastructure planners of *already developed* best available technologies for decarbonisation, and to maximise the use of clean energy in manufacturing processes.

Cement/Concrete

Cement can be decarbonised by reducing the clinker-to-cement ratio, increasing the share of cement alternatives, shifting to electric kilns powered by a decarbonised electric grid supplied with renewable energy, while potentially strengthening concrete through carbon capture and utilisation during manufacturing.

Concrete is the most-used material in the building sector, and the processing of cement, the binding agent in concrete, contributes 7 per cent of global carbon emissions. Because concrete has a developed supply chain and infrastructure, it dominates the industry even where other lower-carbon materials could suffice. Concrete use has grown 10-fold in the past 65 years, compared with a 3-fold increase in steel and near-stagnant growth in timber. Currently, less than 1 per cent of concrete is made from recycled materials, so incentivizing the production of factory-produced modular concrete that is designed for re-use should be prioritised.

As much as 25 per cent of emissions from cement and concrete can be readily saved by adapting building codes and by educating architects, engineers and builders to use the best available technologies. Substituting cement and concrete with bio-based and/or earth-based building materials is also key. The highest priorities for decarbonizing cement production are: reducing the clinker-to-cement ratio; electrifying production with renewable energy sources; scaling innovative but nascent technologies (carbon capture and storage, binders made from alternative materials); and increasing (or mandating) pre-fabrication of circular units that can be disassembled and re-used for future building.

Steel

In primary steel production, a shift from blast furnace to direct reduced iron technology, coupled with electric arc furnaces powered by renewable energy sources, offers the greatest emission reduction potential, together with increasing recycling efficiencies and carbon capture and storage.

Steel is the second most abundant material used in buildings, and embodied emissions from the iron and steel industry represent 7.2 per cent of global greenhouse gas emissions. Avoiding raw material extraction by promoting steel reuse and recycling is the highest priority, since producing steel from scrap saves around 60-80 per cent energy. However, there is a growing gap between supply and demand for both reusable steel components and scrap material for recycling. Shifting from blast furnaces to direct reduced iron technology could reduce the CO_2 emissions from primary steel production 61-97 per cent over the next 15-20 years, far exceeding the emission savings from moving to best available technologies (26 per cent), particularly if coupled with a shift to renewable electricity sources. Other effective measures include reducing steel demand through extending building lifetimes, and substitution with circular bio-based materials such as engineered timber and bamboo.

Aluminium

Aluminium production is highly energy intensive, and with electricity being its dominant energy source, decarbonizing the electricity grid has the largest potential in this sector.

Around 27 per cent of all aluminium produced is used in buildings and construction. Aluminium production is highly energy intensive when produced from ores, whereas producing aluminium from scrap can reduce the energy demand by 70-90 per cent. In 2019, only 34 per cent of aluminium was produced from old and new scrap due to the rapid growth in demand and the long lifetimes of aluminium products. By 2060, aluminium production could be mostly based on scrap, and production could be electrified using renewable energy sources. The integration of aluminium in building systems is skyrocketing, and decarbonizing aluminium will require near-zero-emission technologies for refining and smelting.

Plastics

Increasing plastics recycling requires improvements in collection, sorting, and the predominant mechanical recycling, plus major advances in chemical recycling.

Plastics are ubiquitous materials with high growth rates and low recycling rates of less than 10 per cent. Most greenhouse gas emissions stem from primary resin production (61 per cent), followed by conversion processes (30 per cent) and end-of-life processing (9 per cent). Plastics accounted for 3.4 per cent of global greenhouse gas emissions in 2019, and in 2015, 16 per cent of plastics in the United States of America were used in buildings and construction. Plastics are used in applications from plumbing pipes to window frames, insulation, lining, building textiles and packaging. A shift towards improved methods of plastics recycling, complemented by novel bio-based and biodegradable plastics wherever possible, requires major support for advances in plastics production and recycling.

Glass

The highest initial priority for glass should be decarbonizing production and enabling window glass recycling.

The use of glass could continue in similar quantities as today, or even increase as a replacement material, provided that there is greater support for locally produced and recycled sources, and that the improper design of glass façades does not increase cooling requirements during building maintenance due to increased solar heat gain. Conversely, the transparency of glass will continue to be critical for on-site solar energy collection technologies for roofs and façades, such as daylight harvesting, solar hot water collection and purification, and solar-to-electric systems. Increasing re-use and recycling will require much stricter legislation. Options for decarbonizing glass production include switching the energy source, electrification of all processes, process intensification and waste heat recovery. In renovation and deconstruction, off-site window disassembly avoids contamination and allows for glass recycling.

Earth-based Masonry

High quality earth-based masonry has potential to replace concrete in many low-rise applications but needs development and regulation.

Diverse earth masonry materials made from clay-rich soil and natural fibres, that are dried in the sun or fired, have been used for much of human history and are often re-used. However,

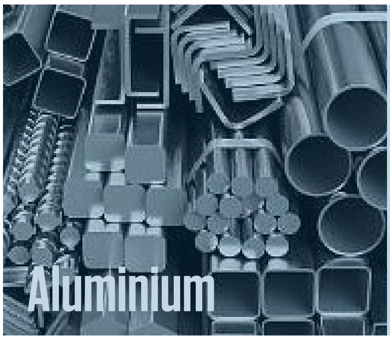
TABLE 0.1

SUMMARY OF DECARBONISATION STRATEGIES PER MATERIAL

NON-RENEWABLE MATERIALS

- Improve quarry rehabilitation and biodiversity restoration of landscapes.
- Reduce the clinker-to-cement ratio with alternative materials.
- Use recycled aggregates.
- Electrify kilns and use renewable electricity sources.
- Integrate carbon capture and storage to provide additional strength.
- Minimize waste with computational design-for-disassembly and re-use.
- Minimize on-site waste and emissions through pre-fabrication.
- Educate building design professionals in material efficiency, optimization.
- Develop standards and building codes that require modular concrete.
- Incentivize renovation over demolition and building codes for recycled.

- Shift from blast furnaces to direct reduced iron (DRI) technology.
- Electrify all steel production methods with renewable energy sources.
- Reduce steel use through a combination of material efficiency measures.
- Avoid using new steel by substituting with re-used (best) and recycled materials.
- Shift to low-carbon alternatives such as bio-based materials if possible.
- Adapt building codes to avoid overspecification and optimize structures.
- Design with pre-fabricated elements for disassembly and re-use.
- Include material efficiency training in the curricula of architects and engineers.
- Ensure that stakeholders across the value chain use the same metrics.
- Improve recycling methods to enable the recovery and use of more steel.



- Reduce demand for new aluminium by promoting re-use and recycling.
- Use electricity from renewable sources (including hydropower).
- Impose strict regulations to design for the circularity of component parts.
- Standardize aluminum alloys/components for re-use.
- Avoid overspecification and use of primary source material.
- Electrify heavy construction and transport equipment.
- Specify high-performance building envelopes.
- Maximize recycling and invest in alloy-specific sorting and recycling.
- Certify disassembled and re-used components.

- Avoid the production of non-recyclable products that harm the biosphere.
- Reduce the use of plastics in building materials, where feasible.
- Use bio-based and bio-degradable plastics produced with renewable energy.
- Design for disassembly and re-use.
- Standardize the chemical compositions of polymers for ease of recycling.
- Increase transparency and/or standardize chemical compositions.
- Trace material usage to keep track of available stock.
- Increase material life with low-carbon maintenance practices.
- Invest in much greater collection, sorting, and mechanical recycling to avoid production of new plastic, complimented by improved chemical recycling.

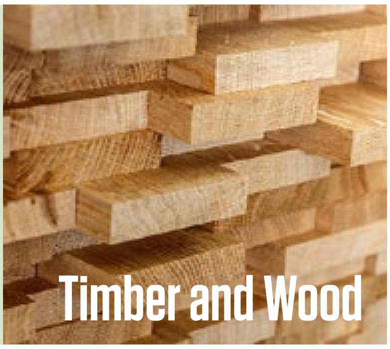
- Avoid new demand by extending lifetimes of buildings and components.
- Incentivize and support locally produced and recycled glass sources.
- Improve research on efficient melting techniques to avoid emissions.
- Shift glass production to best available technologies and recycling.
- Electrify production, construction, and transport with renewable energy.
- Use process intensification and waste heat recovery.
- Design standard components and façade surfacing for recycling, re-use.
- Design glass façades that minimize heat absorption and reflection and instead capture solar energy for heating, cooling, water and lighting.

TRANSITIONAL

- Regulate quarry closure to restore natural landscapes.
- Use structural and facing brick to increase longevity and reduce maintenance.
- Replace high-carbon cement binders with lower-carbon alternative binders.
- Use cement/mortar alternatives, such as fly ash waste and sewage sludge ash.
- Design masonry units for disassembly and re-use.
- Incentivize local, low-carbon earth masonry making.
- Educate design professionals in methods to enhance the longevity of non-stabilized earth masonry.
- Incentivize renovation over demolition.

RENEWABLE MATERIALS

- Incentivize forestlands owners to develop sustainable management and biodiversity.
- Improve the design of forest byproducts, to improve circularity in timber.
- Improve collection rates of "clear-cuts" from logging practices and off-cuts from wood manufacturing for wood products.
- Improve wood manufacturing to capture loss from timber processing.
- Promote and incentivize the use and re-use of structural mass timber.
- Train and upskill construction actors in design-for-disassembly wood.
- Update building codes to mandate reliably certified products.
- Incentivize the research and development of non-toxic glues and binders.



- Increase policy support for commercial enterprises transitioning to highly productive and sustainable bamboo forest management.
- Improve bamboo plant propagation methods.
- Transition bamboo manufacturing to on-site renewable energy.
- Promote material efficiency by developing structural standards for different regional species and circular design.
- Incentivize the use of non-toxic chemicals and glues.
- Integrate and/or adapt bamboo standards for local building codes.
- Educate architecture, engineering and construction professionals.

- Integrate intersectoral biodiverse biomass supply chain management.
- Incentivize and invest in technologies and bioadhesives.
- Redirect biomass towards higher-value end-of-use products.
- Create financial incentives for the capture of biomass building materials.
- Educate and train built environment professionals in design.
- Educate stakeholders on effective maintenance of products.
- Educate finance and insurance companies to incentivize adoption.
- Implement marketing and education programmes.
- Train and upskill material recovery management to improve re-use rates.

- Understand native ecological systems and context before introducing new living biomass material; Use native species and organic fertilizer.
- Adapt district-scale carbon incentives for impacts to urban heat island and stormwater infrastructure.
- Design with low-carbon material substructures, growing media, passive solar energy, and harvested rainwater for irrigation.
- Provide avenues for circular compost and waste by-product recovery.
- Minimize material use through the optimization of structures.
- Minimize weight of materials by using less water and soil.

increasingly masonry bricks have adopted the use of high-carbon cement binders and high temperature firing to address mechanical and moisture performance. If locally made with low-carbon binders, additives and processing methods, earth masonry can regain its role as a viable building material for many regions and applications.

Emerging economies have a critical opportunity to leapfrog over the carbon-intensive building methods of developed regions

Emerging economies are in the midst of an unprecedented global construction boom, and the window for transforming building materials and methods is narrowing. As the world economy expands and as living standards rise, the global use of raw materials is projected to nearly double by 2060, under a business-as-usual scenario. Floor space worldwide is set to double by 2060, and every five days the world constructs enough new buildings to add another city the size of Paris. However, as humanity continues to build more rapidly than ever in the quest to secure comfort and well-being, there is an important opportunity for developing countries to leapfrog over the unsustainable building technologies of the last century, if binding commitments are made to ensure the cooperation of essential stakeholders across the supply chains, from producers and growers, to designers, builders and owners.

Strategies to Align Stakeholders Across the Whole Life Cycle to Ensure Global Cooperation on Decarbonisation

The built environment sector has the potential to rapidly decarbonise if synergistic measures are taken to support diverse stakeholders across the life cycle of materials – a life cycle that spans across international supply chains. Rapid decarbonisation of building materials will not be possible without simultaneously supporting material producers and users such as manufacturers, architects, developers, communities and building occupants, to make the decision to decarbonise. Due to the complexity of this interconnected sector, regulation and synergistic enforcement is required across all phases of the building life cycle, from extraction through end-of-use.

Novel ownership models that reconcile the currently 'split' incentives between producers, builders, owners and occupants should be encouraged in order to enhance cooperative models in creating circular economies, especially for high value extracted materials such as non-renewable metals. The creation of novel future ownership models should be encouraged with investment. For example, as with renewable energy and vegetation systems, production and construction consortiums could 'lease' and/or maintain facades or other high value added material components and maintain them throughout a building lifecycle, in order to incentivise their ongoing productivity, longevity and/or reuse of materials at 'end-of-life'.

1. Improve and Increase Access to Reliable, Transparent Data

Common metrics and consistent assessment processes allow decision-makers to accurately weigh the trade-offs among alternative decarbonisation pathways and inform efforts to set standards and trade policy. However, tools to visualise and assess data need to be more accessible, transparent and verifiable to all stakeholders. Whole life-cycle assessments combine embodied carbon with anticipated operational carbon, but the impacts on global ecosystems remain widely under-estimated.

A wider range of tools are emerging to help decision-makers gain easier access to the right data to assess the carbon impacts of their building material choices; however, tools and access to transparent quality data needs to be prioritised, with the burden of including smaller actors shared by formal and developed sectors.

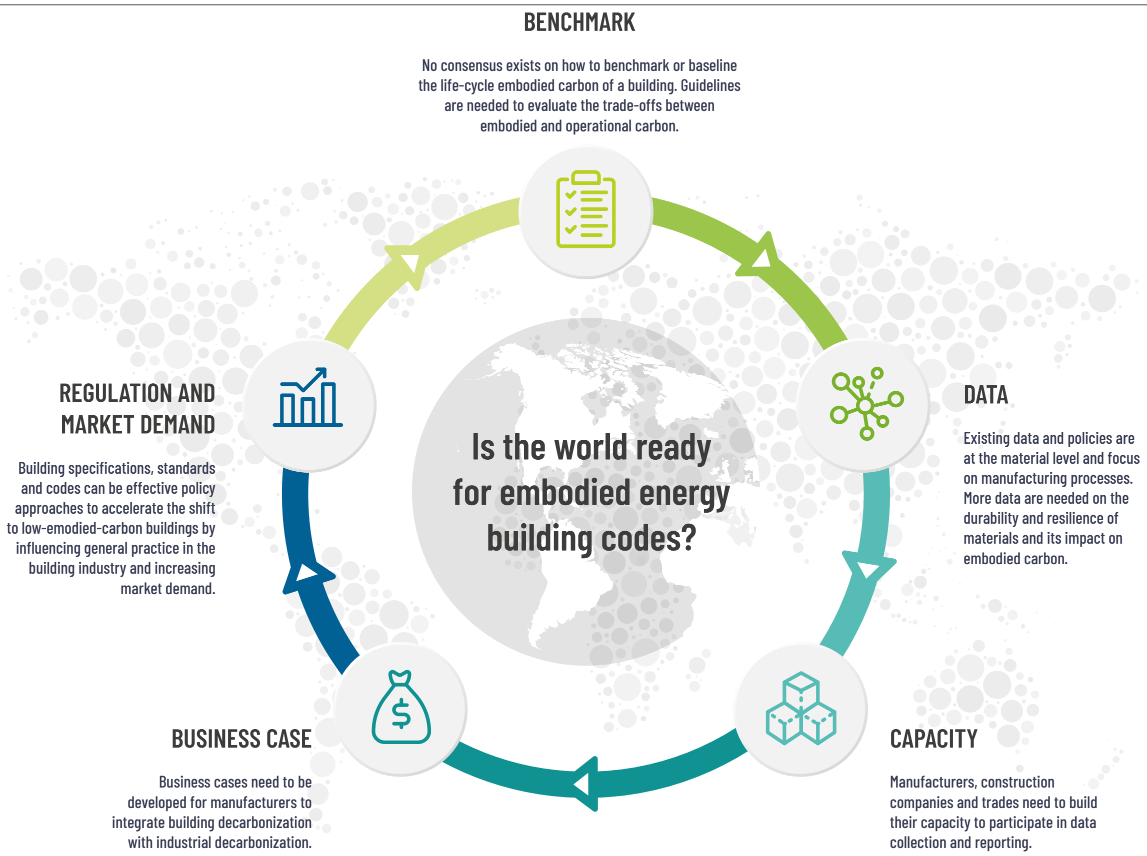
With the right access and training, readily available tools for managing, visualising and communicating the data behind decisions can be game-changing. Tools and frameworks could enable comparison of the pros and cons of different building materials in terms of their embodied, operational and end-of-life climate greenhouse gas emissions. Data management and visualisation tools are emerging that offer "at-a-glance" scenarios to support decision-making in real time.

However, as with environmental assessments and certifications across all sectors, the verifiability and consistency of data remains a huge challenge. The significant range in the quality and quantity of data and certification processes across all material sectors, even the most developed ones, results in uncertainty on the part of material specifiers, especially amongst disadvantaged smaller actors. Moreover, the challenge across all global sectors, from informal to formal construction, is to get the right data to the right stakeholders at the consequential stages of decision-making. For the latter, there is potential to better harness building information models from the design and construction phases, in order to better track the impact of material decisions on the life cycle.

2. Increase Inclusion and Ensure Fairness in Certification and Labelling Standards

Rising public interest in environmentally sound construction practices has led to a flood of self-declared environmental claims from material producers, with limited traceability

0.1 Municipal building energy codes need to transition to include embodied energy



Various requirements and challenges are necessary for such a transition.

Source: Adapted from American Council for an Energy-Efficient Economy 2021..

– generating scepticism and backlash. International cooperation is required to regulate fair certification, verification and labelling for trade across borders and regions. For true decarbonisation of global material flows, it is necessary to close a "carbon loophole" that disadvantages producers facing strict pollution controls. In turn, it is critical to help smaller producers, especially in emerging economies, to achieve certification, as they are often unfairly penalised with cross-border carbon taxes because they cannot afford, or lack access to, fair certification processes.

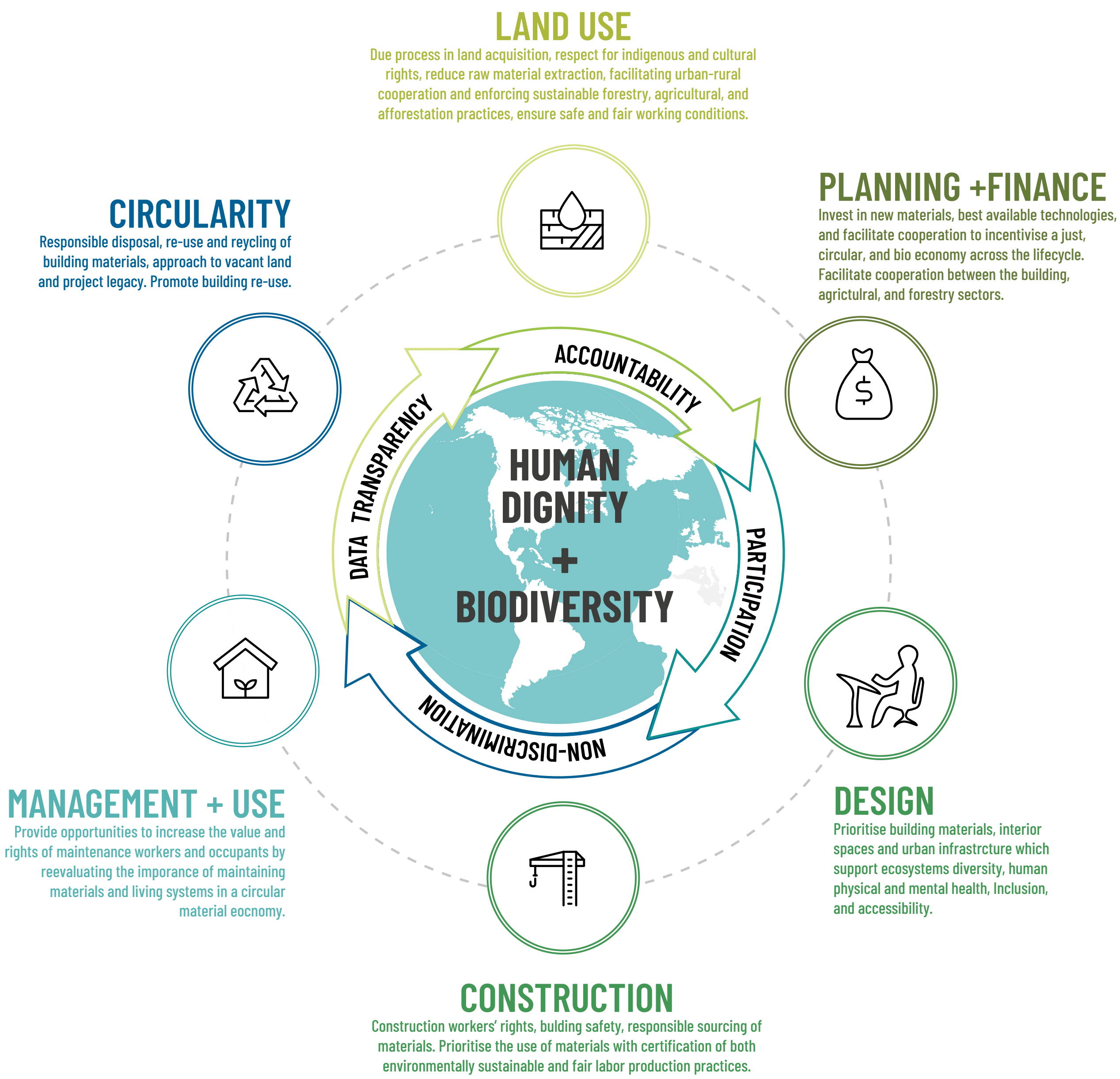
3. Enforce Performance-Based Building Codes

With the growing adoption of low-cost, digitised tracking methods and access to demand-side metrics such as energy and water use, performance-based building codes have a greater chance to connect to a range of stakeholders across sectors, as they see the impact of their choices affect their finances and wellbeing. However, several key impediments still need to be addressed for widespread inclusion of embodied carbon in building codes, alongside the impacts of material choices on global ecosystems and the work of the geo-biosphere.

4. Empower cities and municipalities as drivers of change to Implement Decarbonisation at the District Level

Governments must improve multilevel governance frameworks and mechanisms to better implement and enforce buildings and construction regulations which support whole lifecycle approaches and low carbon material efficiency strategies. Cities must be empowered to implement and enforce decarbonisation policies in collaboration with national and sub-national government institutions as part of their local action plans for buildings and construction. They need to promote sustainable energy solutions and encourage passive design, circularity, nature-based and neighbourhood level solutions, incentivizing buildings and construction industry stakeholders as change agents. As champions for implementing and enforcing climate policies and targets, cities are uniquely placed to catalyse this transition through their jurisdiction over land use, authority over housing programmes, role in implementing national policies and building codes, and their role in coordinating with local utilities and stakeholders.
The public sector is often in the best position to implement decarbonisation plans at local or district scale. It can have maximum impact for new development, since strategies for

Figure 0.2 Humans are Part of Living Ecosystems: Framework for dignity across the built environment lifecycle



Source: Partially adapted from Institute for Human Rights and Business (2022).

individual buildings can be integrated in synergy with the design of sustainable, electrified grids for the management of energy, water, waste and transport. Policies and ambitious targets from local and national governments establish leading precedents for integrated decarbonisation across multiple scales of infrastructure and buildings. This is only possible if material choices and urban planning avoid driving up cooling demands through the creation of urban heat islands and instead lowers the overall operational carbon of cities by mandating biomass materials and other cool surfaces.

5. Harness Public Procurement to Support Decarbonisation of Materials

In many emerging economies, the public sector can play a critical leading role in demonstrating and enabling building material decarbonisation through its procurement powers. However, policy goals for decarbonisation must be formally linked to the purchasing of materials planning phases with rigorous whole life-cycle assessments to serve as examples for effective solutions across specific local climate types and building traditions.

6. Tackle Gender Bias in Both Formal and Informal Building Sectors

Gender bias is prevalent across the different phases of the built environment process. In many formal sectors, the two principal issues to act on are: 1) closing the large gender pay gaps that persist across the architecture, engineering and construction industries, and 2) addressing the overwhelming dominance of men in senior decision-making and administrative roles. Across informal sectors, the urgent priorities should be: 1) enforcing national and municipal regulations for safety and improved working conditions at construction sites, and 2) promoting skill development among casual labour to enable the transition to fairer and more consistent labour conditions. 3) In the shift towards bio-based materials, critical attention should be placed on protecting ecosystems and workers from toxicity and environmental degradation from unsound agricultural and forestry practices.

In the context of many emerging economies with a preponderance of semi-formal and informal construction, governmental programmes and policies need to expand women's access to new technologies, marketing information and training to sustain their participation on the ground. Given that women face barriers to accessing credit and loans, financial institutions need to service and design loan collateral systems that are suitable to individuals and women collectives.

Ensuring Reliable Data

In order to galvanise the market and to enable designers, building owners, and communities to make the right decisions, tools to support the decarbonisation of building materials require more rapid progress. These tools must be supported by access to better quality data and transparent audits conducted by qualified third-party reviewers. More synergy could be leveraged in combining the certification of fair labour and environmental practices / working conditions. In the informal sectors, stakeholders typically have neither the access to data nor the means to conduct analyses or certification, thus greatly disadvantaging both producers and builders in emerging economies from decarbonizing their output, for both local and export markets.

Significant investment in the research and development of methods and standards is required, towards better models of coordination across producers, designers, builders, and communities, and with regulation of fair certification and labelling. The biggest challenge to these measures is the complexity and lack of transparency of international supply chains for building materials. Furthermore, there are substantial risks that need to be avoided in the shift to bio-based materials. The biodiversity and wellbeing of regions must be improved not degraded, with indigenous populations, women and children being most at-risk of exploitation and toxic exposures in the agriculture and forestry industries, potentially compounding the existing gender inequities in the conventional building sectors. Conversely, multiple studies show that the presence of women in decision-making positions is correlative with a communal and cooperative focus on sustainable resource management in many regions. The variability of climates, agricultural practices and species adds to the complexity of fair certification and global trade. Hence, international cooperation across borders is essential towards ensuring a just transition with regenerative environmental and labour conditions.

Thus, international cooperation is critical to support fair certification and labelling. Such policies can be synergistic with improving strategies to decarbonise the embodied energy of materials within the formal sectors across the globe, as these are the sectors that are producing the majority of carbon emissions in the built environment today. Thus, the responsibility for seeding a new marketplace and galvanising a future net zero economy for the built environment sector should be spread across producers and consumers within the formal global building sectors, both public and private.

POLICY RECOMMENTATIONS FOR DECARBONISING MATERIALS IN THE GLOBAL BUILDING SECTOR

TO UNBLOCK RESISTANCE, POLICY MAKERS MUST ENGAGE ACTORS ACROSS THE VALUE CHAIN

In summation, wholesale decarbonisation of building materials will not be possible without supporting and regulating synergistic measures across the supply chain and lifecycle of the different material sectors, from extraction through end-of-use and circular reuse. Policy makers must engage actors across the entire value chain towards the three main decarbonisation principles discussed in this report: 1) Avoid material overuse and new material extraction by building (with) less, actively seeking ways of reusing and recycling buildings and materials; 2) Shift to sustainably produced low carbon renewable building materials such as earth and biobased materials whenever possible; 3) Improve methods to decarbonise carbon-intensive conventional materials such as concrete, steel and aluminium, and only use them when necessary.

Across regions, implementation methods will vary as patterns in material flow scenarios differ. In highly developed regions, incentives need to focus on the renovation of existing and ageing building stock, whereas in developing regions with rapid rural to urban migration, and rampant housing insecurity, there is an opportunity to radically re-invent new construction techniques and leapfrog over prior modern practices by reconnecting with existing, local climate-specific building knowledge and vernacular traditions, while dramatically improving conventional material production, and shifting to sustainably sourced biomaterials wherever possible.

To drive market transformation and stakeholder action, governments should take action to:

1. Set the Vision, Lead by Example and Improve Multi-Level Governance

- Develop national and sub-national roadmaps and action plans and institutionalising coordination mechanisms to facilitate collaboration between actors and ensure that these are not affected by short-terms political cycles.
- Empower cities and municipalities as drivers of regional change by unde

2. Make Carbon Visible through Improved Data Access and Quality

- Promote clear and consistent standards for carbon labelling. Products should be certified with international standards such as the GHG Protocol Product Standard, ISO14067 or PAS2050, with more support for enforcing fair regulation.
- Mandate the lifecycle assessment (LCA) of the carbon impact of building materials and fund research to determine best practices for life-cycle analysis of ecosystem impacts.
- Purchase, provide or subsidise data needed for assessments for key stakeholders.
- Dramatically increase the support for ongoing tool development and use for stakeholders across the supply chain to be able to make rapid and reliable design and procurement decisions.
- Encourage digitalisation and the development of building passports to assist in standa rdising data to be traceable, transparent, and verifiable.
- Fund research to further develop data banks.

3. Adapt norms and standards to allow for the use of circular, alternative or lower-carbon, bio-based building materials and construction practices

- Introducing/strengthening performance-based building codes that include embodied carbon, mandating the transition to low carbon (and renewable, if possible) materials.
- Accelerate the industry transition by supporting the rapid decarbonisation of conventional materials, through electrification with renewables and dramatically increasing the R&D budgets and public-private partnerships towards innovation of circular, decarbonisation and carbon capturing technologies.

4. Incentivise Circular Economy Approaches for Re-Use and Recycling

- Incentivise building designs that last as long as possible and, where possible, incorporate design for disassembly and modular construction to facilitate end-of-life recycling .
- Adopt renovation policies that encourage the diversion of end-of-life material for recovery and recycling, promote regulation and measuring of whole building life-cycle carbon emissions, incorporate design for disassembly, and provide quality long-lasting material assemblies in retrofit solutions.
- Promote the consideration of end-of-use strategies during material specification in the design of new buildings and renovation solutions to avoid waste and associated emissions later in the building life.
- Incentivise a marketplace for material re-use and develop standards to ensure the quality and efficacy for their use, in order to provide assurance to actors in the building sector.

5. Promote the Transition to Low-Carbon, Biodiverse Materials

- Adopt both "push" and "pull" market approaches to scale up sustainable bio-based building materials, by pushing to create consumer demand by supporting low-carbon building material enterprises at the local and bioregional level to develop and market new products, whilst cultivating broad public interest and education through powerful advertising and public education campaigns.
- Accelerate international and local regulatory frameworks to normalise industry adoption of bio-based materials, including by standardising material performance criteria, integrating these materials into building codes and training stakeholders in the mainstream construction industry.
- Dramatically reduce the risk of regional forest fires and increase the carbon sequestering productivity of regional forests and agricultural lands by facilitating education and investment in enterprises focused on collection, clean incineration and upcycling of forest, agricultural and biomass resources towards integration into binders, finishes and structural products.

6. Ensure a Just Transition

The transition to bio-based and circular material economies may exacerbate these risks across the supply chain, especially in informal economies where building codes are extremely difficult to enforce. Therefore, it is crucial that governments seize the opportunity of coupling social and environmental justice with fair and visible labelling and certification processes to raise awareness among consumers, since the two issues combined may ultimately have greater market 'pull' than either issue labelled separately.

- Engage stakeholders across the supply chain by funding just transition programs, labelling and certification.
- Anticipate and fund problem areas for a just transition, particularly in conventional high-carbon material sectors.
- Highlight and encourage the resolution of existing inequities.
- Promote the widespread use of Just Transition planning Toolkits such as by Climate Investment Funds and Design for Freedom.
- Support industry to secure workers and their communities affected by downscaling of conventional processes and encourage synergies with new opportunities and replacement methods that are biobased or circular.
- Encourage inclusive and transparent planning.
- Strengthen international action and collaboration for collective impacts.
- Incentivise gender inclusion in government contracts and prioritise project approvals for companies that promote women to leadership positions.
- Enforce national and municipal regulations for safety and improved working conditions at construction sites..

7. Strengthen International Action and Collaboration for Collective Impact

- Promote clear and consistent standards for carbon labelling.
- Ensure that regulation and enforcement of domestic carbon labelling matches ISO standards.
- Establish an international standards committee for carbon impact labelling of building materials to address discrepancies in methods and quality and create pathways towards enforceable regulation.
- Close the "carbon loophole" in carbon offsets by developing a sliding scale of relevance, whereby the process

NEW ECONOMIC MODELS ARE REQUIRED THAT ENHANCE COOPERATION AND REPAIR SPLIT INCENTIVES ACROSS STAKEHOLDERS

most closely associated with the actual decarbonisation of material processes gets the most credit.

- Develop trade mechanisms to support emerging economies.
- Ensure a fair playing field for low-carbon building materials through international and multilateral engagement.

In conclusion, the built environment sector must learn to design with nature-based processes if it is to decarbonise. This means reducing the burdens on the geobiosphere from "extracted", toxic, non-renewable materials, and increasing regenerative, renewable and circular materials. However, all material sectors need to be included and policies can create synergistic opportunities for both conventional and emerging industries. For example, decarbonisation of the cement sector and other major emitters can be enhanced by shifting to bio-based binders and other low-carbon replacements.

However, many of these emerging decarbonisation methods are often not yet cost competitive, and widespread biases remain that protect entrenched methods. Sustainably scaling up implementation cannot be enforced without substantial investment in research and development alongside incentives and/or enforceable building codes. Although the shift from extracting to growing building materials presents major opportunities, there are substantial dangers of an unregulated shift towards biomaterials backfiring and causing unmitigated environmental degradation.

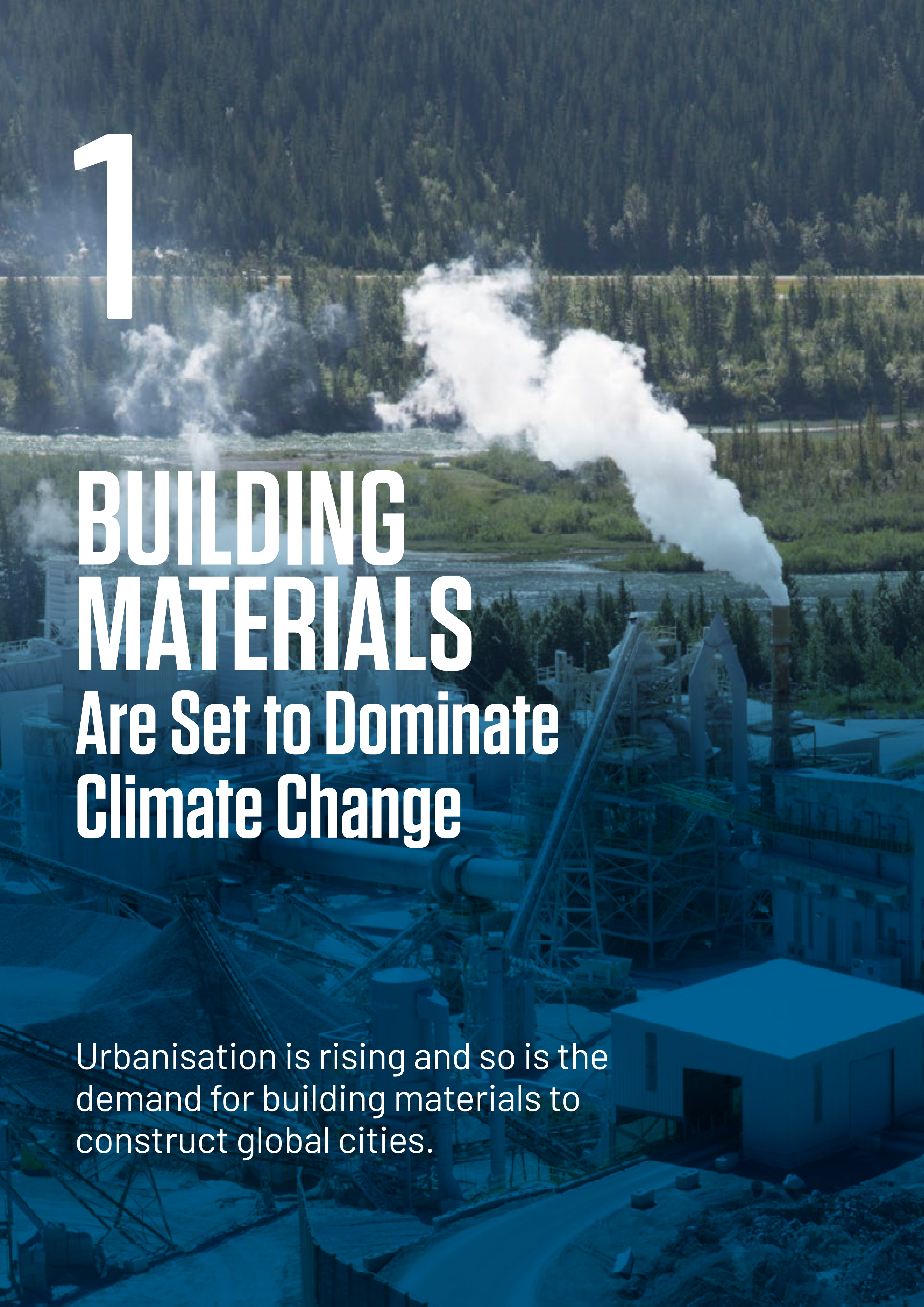
Thus, international cooperation is critical. Policies can be synergistic with improving strategies to decarbonise the embodied energy of materials within the formal sectors across the globe, as these are the sectors that are consuming and producing the majority of carbon emissions in the built environment today. At the international climate level, action is required for countries to address embodied carbon in their Nationally Determined Contributions (NDCs) towards reducing emissions under the Paris Agreement, and the next steps towards ensuring firm commitments need to be legislated through enforceable building energy codes. Despite the massive contribution to global emissions from embodied carbon within building materials, it has previously been under-addressed in strategies to reduce building emissions. Thus, the responsibility for galvanising a future net zero economy for the built environment sector should be spread across producers and consumers within the formal global building sector, both public and private, in order to bolster the transition to a clean, just, renewable, circular building materials economy.

TABLE 0.2

WHO DOES WHAT TO DECARBONISE MATERIALS?

BUILDING LIFE CYCLE PHASES

	POLICY MAKERS	FINANCIAL INVESTORS + DEVELOPERS	MANUFACTURERS, BUILDERS + WASTE MANAGERS	ARCHITECTS, ENGINEERS + OCCUPANTS
WORK OF THE GEO-BIOSPHERE	> Policies to reduce extraction of non-renewable materials > Facilitate innovation in biodiverse, circular forestry and agriculture	> Use economic practices that value natural capital and biodiversity > Commit to gender equity + fair labour across project life cycles	> Avoid unsustainable land-use patterns, soil degradation and forestry practices in sourcing both conventional and bio-based materials	> Consider the source and recovery rate of non-renewable and renewable materials when designing materials
DESIGN	> Enforce performance-based building codes > Develop **fair** green certifications and transparent labelling > Incentivize tools for data-driven design	> Invest in design of recycled, re-used and bio-based materials and components > Invest in accessible data visualization frameworks	> Commit to the development of circular components > Develop materials to optimize recyclability > Develop bio-based alternatives	> Design for longer life > Increase education in decarbonisation strategies > Computation / design / optimization of local materials for re-use
PRODUCTION	> Electrify the grid > Mandate recycling and best available technologies (BAT) > Mandate forest and material management > Improve certifications	> Invest in innovation for low-carbon materials and binders > Invest in new low-carbon methods > Invest in BAT equipment	> Upgrade plants > Avoid primary materials > Circular manufacturing and composites for re-use > Commit to fair labour	> Work with producers to specify circular materials > Design development of alternative bio-based materials and components
CONSTRUCTION	> Mandate green certifications > Mandate third-party verification of site processes and emissions > Incentivize off-site circular manufacturing	> Increase energy-efficient financing > Improve financing for refurbishment and renovation of existing buildings and materials > Commit to fair labour	> Trace material use > Electrify all equipment with renewable energy > Require energy efficiency > Improve training > Commit to fair labour	> Manage on-site waste through pre-fabrication > Improve management of on-site construction with circular design
USE	> Adopt building energy codes that mandate materials supporting high-performance envelopes to reduce operational carbon > Incentivize renovation over new construction	> Develop financial tools to incentivize low carbon material selection by reconizing energy and cost pay-back periods	> Support building owners and occupants to select low-carbon alternatives through supply chain development	> Increase material life with low-carbon maintenance practices > Select materials that reduce operational carbon
END OF USE	> Certify pre-used components > Building codes to mandate re-use > Plan cities to incorporate transfer plants > Regulate demolition	> Provide economic incentives to avoid demolition by refurbishing buildings, increasing re-use and recycling	> Improve recovery and on-site sorting of materials > Standardize materials to improve recycling	> Design for dissasembly and re-Use > Increase continuing education for students and professionals in novel circular material strategies



1

BUILDING MATERIALS Are Set to Dominate Climate Change

Urbanisation is rising and so is the demand for building materials to construct global cities.

1.1 The Built Environment's Impact on Global Carbon Emissions

The built environment sector contributes 37% of energy-related carbon emissions.

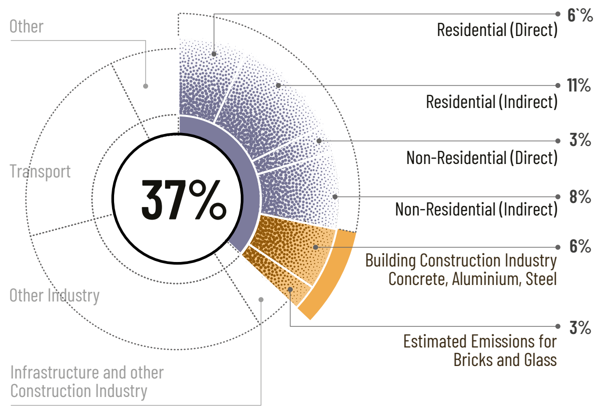
The built environment sector is one of the largest contributors to climate change, responsible for more than a third (37 per cent) of global energy-related carbon emissions (United Nations Environment Programme [UNEP] 2022, see **Figure 1.1**). Yet the built environment has received only a small fraction of climate-focused funding for research and development compared to other sectors. Although investments in the energy efficiency of building operations increased 16 per cent among Group of Seven (G7) countries in 2021 (ibid.), such commitments pale in comparison to what is required to decarbonise the built environment. As the largest global industrialised sector, construction also has widespread social impacts; it is at the highest risk of forced labour, with lax environmental and labour regulations tending to coincide (Grace Farms Foundation 2022).

As both population and wealth continue to grow globally, humanity is building more than ever in a quest to secure comfort and well-being. Floor space worldwide is set to double by 2060, and every five days the world adds enough new buildings to total the size of Paris (UN Environment Programme [UNEP] and International Energy Agency [IEA] 2017). According to a 2019 report from the Organisation for Economic Co-operation and Development (OECD), the global consumption of raw materials will nearly double by 2060 as the world economy expands and living standards rise, doubling the environmental overloading being experienced today. The OECD projects that if we continue "business-as-usual" practices, the biggest increase in resource use by 2060 will be in extractive minerals, particularly in developing economies (OECD 2019).

These megatrends are also influenced by rapid urbanisation. In 2020, the 124 countries that dominate the developing world were home to 81 per cent of the world's population, and this share is projected to reach 87 per cent by the end of the century (Roser and Rodés-Guirao 2013; United Nations Department of Economic and Social Affairs 2020; World Bank n.d.). Much of this future population growth will occur in cities. The World Bank estimates that to meet the rapid increase in urban populations, 300 million additional houses will need to be constructed by 2030 (World Bank 2022a). Enabling this global building boom requires a new agenda for decarbonisation to meet residential needs of developing countries while decarbonizing the full range of building types globally, from formal to informal (see **Box 1.1**).

1.1 Global carbon emissions from the built environment sector, by source, 2021

Global share of buildings and construction operational and process CO_2 emissions, 2021



The built environment sector is responsible for more than a third of global energy-related carbon emissions.

Adapted from UNEP 2022.

In the absence of urgent action, the carbon emissions of common construction materials such as concrete, steel and aluminium are projected to grow to increasingly dangerous levels. Although developed countries have historically contributed the vast majority of global carbon emissions, the world's top 10 greenhouse gas-emitting countries now include rapidly developing countries such as China, India and Iran (Islamic Republic of) (Nejat et al. 2015). Even with the implementation of widely accepted interventions, emissions from the built environment sector are projected to go far beyond what is allowable to keep global temperature rise within 1.5 degrees Celsius, the target set under the 2015 Paris Agreement on climate change (Cao et al. 2021).

This report outlines concrete pathways to reverse these projections, and even to reach net zero emissions in the built environment sector by mid-century, through the promotion of best available technologies for conventional materials, combined with a major push to advance circular recycling and bio-based materials from forest and agriculture streams.

BOX 1.1

THE NEED TO ADDRESS THE FULL RANGE OF BUILDING TYPES GLOBALLY IN DECARBONISATION EFFORTS

By 2030, 3 billion people worldwide are expected to require access to adequate, affordable and comfortable housing (United Nations n.d.). Much of this demand will be in the rapidly urbanizing developing world. However, most global studies on housing growth to-date have focused on formal buildings, including single-family, multi-family and high-rise types found in developed countries (Marinova *et al.* 2020).

Recently, a growing literature is detailing the additional diversity of buildings in developing countries (Pikholz 1997; de Wet et al. 2011; Malik and Bardhan 2018; Mehrotra, Bardhan, and Ramamritham 2018; Nutkiewicz, Jain and Bardhan 2018). One study defined three categories of building types worldwide — formal, informal and semi-formal — with the most common differing characteristics being in construction materials and style, size, durability and demography of the residents (see **Table 1.1**) (Iyer, Rao and Hertwich 2023). As of 2016, more than 1 billion people lived in informal housing slums and lacked access to durable housing, along with other basic amenities (UN-Habitat 2016).

© Adelaide & Rural Salvage

Table 1.1 Categorization of buildings worldwide based on durability and other factors

	Formal	Semi-formal	Informal
Durability	High	Medium to low	Low
Construction	Reinforced	Not fully reinforced	Not reinforced
Number of floors	No restrictions	Two to three	One to two
Income class of residents	Middle to high	Low to lower-middle	Low

Source: Iyer, Rao and Hertwich 2023.

Because formal buildings are typically more durable than the other two types of buildings (Iyer, Rao and Hertwich 2023), many low- and middle-income countries seek to redevelop informal homes and to relocate residents to new, formal constructions (Kharche 2020). However, studies have shown that residents in semi-formal and informal housing often have thriving social lives and a sense of community (Bardhan *et al.* 2018; Sanyal n.d.), whereas in formal apartment buildings they may be more isolated socially (Debnath, Bardhan and Sunikka-Blank 2019). Resettled inhabitants often end up moving back to informal settlements from their new formal homes, whether for social reasons, to be close to workplaces, to reduce costs or other factors (Debnath, Bardhan and Sunikka-Blank 2019).

Moreover, redeveloped formal buildings are often poorly designed and rarely take into consideration the preferences of relocated residents. Insufficient cooking and outdoor space and poor aesthetics are common issues faced by residents, adding to their motivation to move back to horizontal slums (Debnath, Bardhan and Sunikka-Blank 2019). Based on these findings, policymakers need to ensure stakeholder participation in decision-making processes, especially pertaining to slum redevelopment. Being aware and inclusive of the lifestyle, needs and unique constraints faced by these low-income inhabitants might improve redevelopment success rates.

However, a complete rehabilitation of informal settlements is unlikely. Thus, research needs to focus on improved materials in the building envelope, improving thermal comfort for inhabitants and reducing life-cycle energy demand. Additionally, retrofits with low-cost passive cooling materials must be investigated for informal and semi-formal buildings, to provide thermal comfort in the transition towards more durable homes. This is especially key as these low-income homes perform especially poorly in providing thermal comfort in a heating world, as inhabitants are priced out of common mechanical cooling technologies and appliances.

1.2 We Used to Build with Low-Carbon Materials

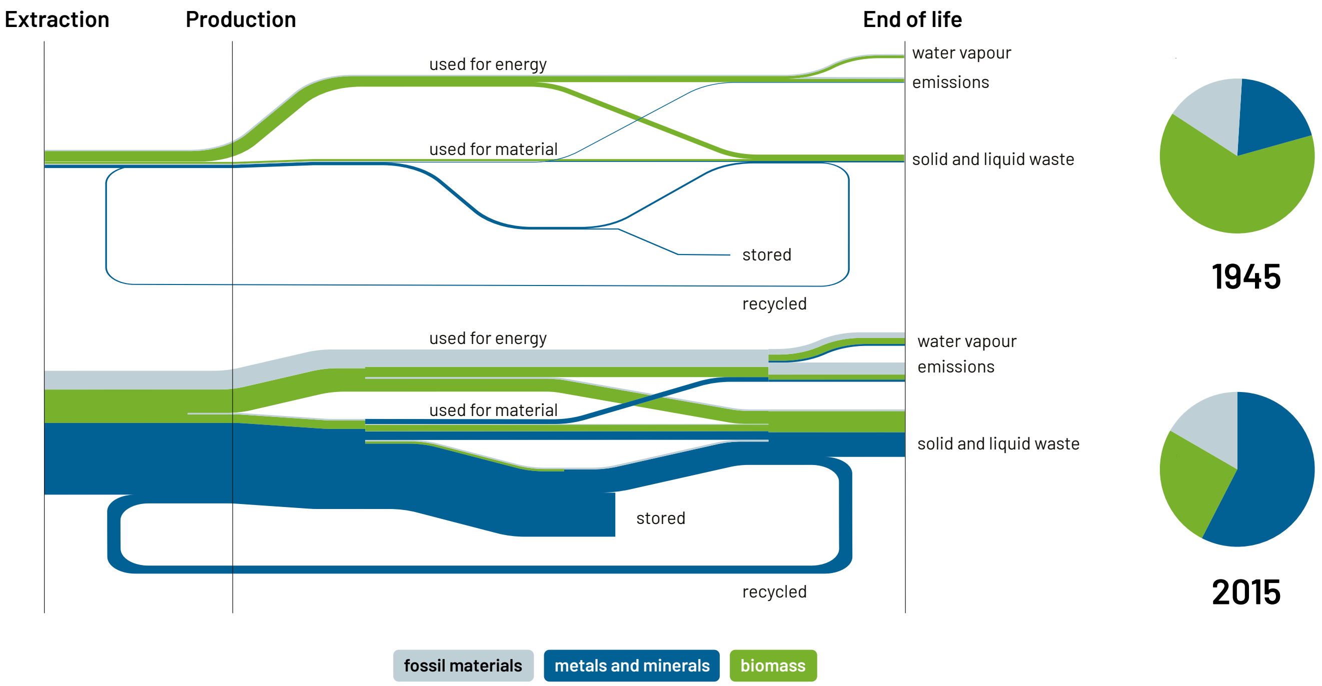
Even in the very recent past, building materials were not always carbon intensive.

Given the increasingly furious pace and scale of the global cGiven the increasingly furious pace and scale of the global construction boom, the challenge of shifting away from carbon-intensive materials and methods often seems daunting and potentially impossible. But it is important to recall that even in the very recent past, building materials were not always carbon intensive. Up until the mid-20th century, global material flows were extracted overwhelmingly from renewable, biological sources such as forests and agricultural processes (see **Figure 1.2**). The vast majority of building materials were locally sourced, and buildings were specifically designed with climate conditions in mind.

Biomass materials – including wood and timber – dominated global construction, alongside earth-based materials, until the latter half of the 20th century. It has only been in the last several decades that the majority of building materials come from extractive, toxic, non-renewable processes. By the late 20th century, a preponderance of metals and minerals constituted the most-used building materials for the first time in human history. Just three materials – concrete, steel and aluminium – are responsible for 23 per cent of overall global emissions today (Global Alliance for Buildings and Construction [[GlobalABC], International Energy Agency [IEA] and UNEP 2019). With cooperation across global sectors, we can alter this path. The shift towards properly-managed biobased materials could lead to a compounded emissions savings in the sector of up to 40 per cent by 2050 in many regions.

To enable the shift towards new methods, it is important to understand what drives the decisions being made at each phase of the built environment process. Building materials carry enormous cultural significance. The reasons that societies choose to build with certain materials over others are complex and are driven by diverse social, technical and economic factors. Common carbon-intensive materials such as bricks, concrete, steel and glass are responsible for the image and cultural currency of cities, institutions and houses. They reflect how a community has organised over time and what it has valued during different periods of its history. Inside buildings, where modern society increasingly spends the most time, interior finishes such as wood, plaster and ceramics define the "look and feel" of how people experience their homes and workplaces, with significant implications for health and well-being.

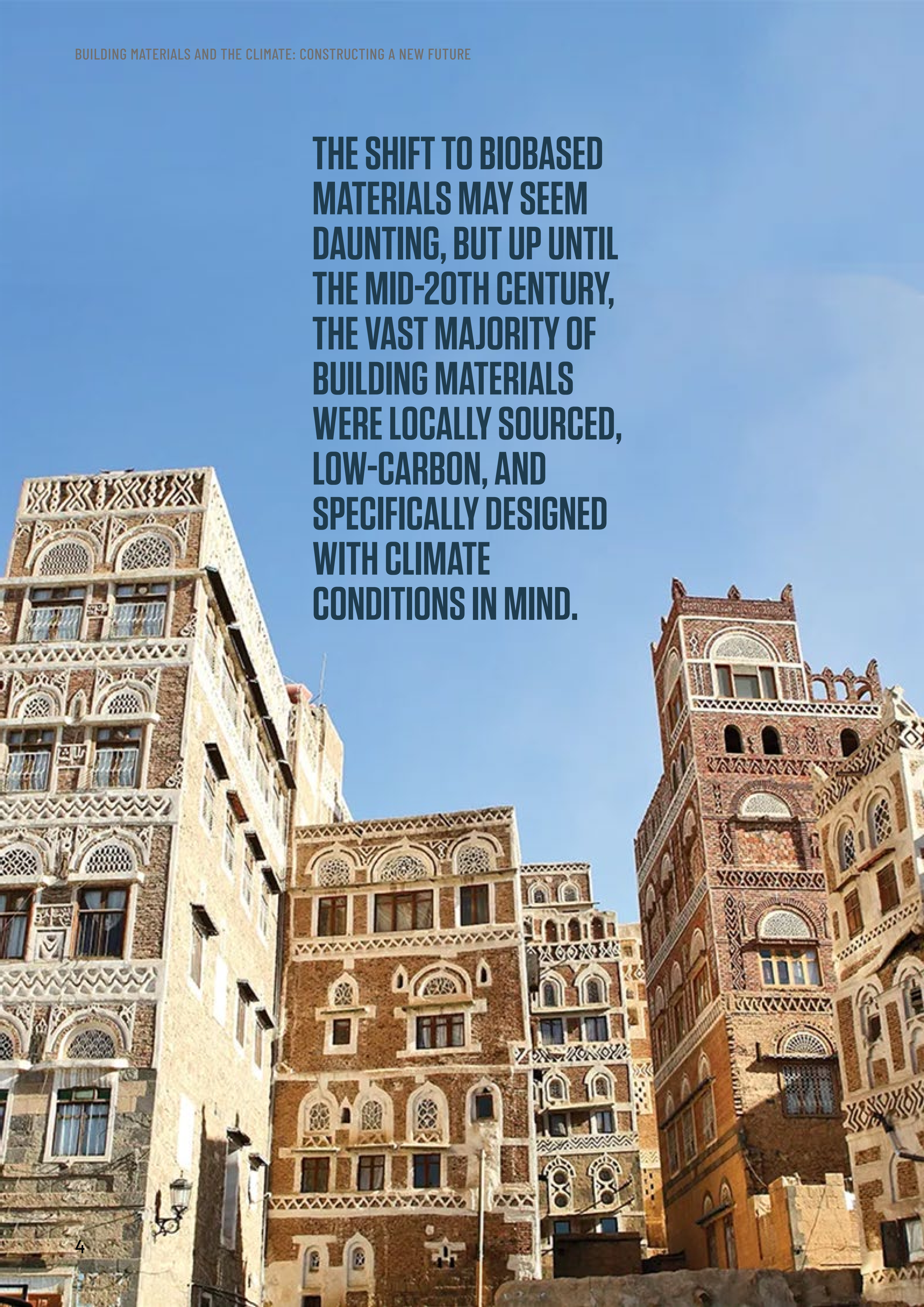
1.2 Global material flows, by type, 1945 versus 2015



Biomass materials dominated in buildings until the latter half of the 20th century.

Source: Haas et al. 2020.

THE SHIFT TO BIOBASED MATERIALS MAY SEEM DAUNTING, BUT UP UNTIL THE MID-20TH CENTURY, THE VAST MAJORITY OF BUILDING MATERIALS WERE LOCALLY SOURCED, LOW-CARBON, AND SPECIFICALLY DESIGNED WITH CLIMATE CONDITIONS IN MIND.



1.3 Structure of the Report

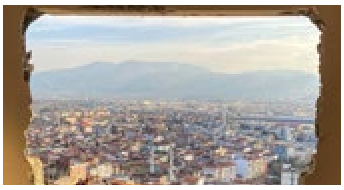
This report is organised in the same manner required for building decarbonisation. Because buildings are integrated systems, comprising many materials produced in disparate regions across the globe, there is no single strategy. Rather it is important to carefully cultivate the ability for decision-makers to take synergistic measures across multiple material sectors and at multiple stages in the lifetime of buildings. This report offers a guide to applying a "whole life-cycle approach" to the built environment sector and gives decision-makers a set of compounding strategies to apply.

2 LIFE CYCLE THINKING

Chapter 2 provides background on the main sources of carbon emissions from the built environment sector – embodied and operational emissions – and outlines high-level strategies for adopting a whole life-cycle approach to the built environment, particularly around embodied carbon and building material choice.

3 AVOID

Chapter 3 provides specific guidance for key actors about what actions should be taken in what context and along what timeline to achieve maximum decarbonisation through circular material strategies. It focuses specifically on the strategies of avoiding waste, building (with) less and improving circularity.



4 SHIFT

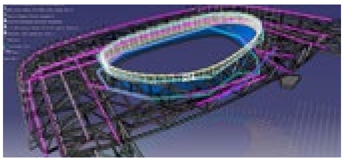
Chapter 4 considers the full implication of a revolutionary shift towards bio-based materials – with all of the potential pitfalls and necessary technological developments that must be supported in order to successfully scale up low-carbon biomaterials while achieving net biodiversity.

5 IMPROVE

Chapter 5 looks carefully at the range of conventional building materials choices, their carbon impacts across their lifespans, and important technological and market shifts and trends associated with them. It focuses specifically on ways to improve their production and use (when necessary) in order to decarbonise conventional material processing.

6 TOOLS

Chapter 6 provides information on existing and emerging analytical tools for assessing carbon impacts across the entire building life cycle. It outlines the need for district-scale planning and global standards and labels for emission transparency.



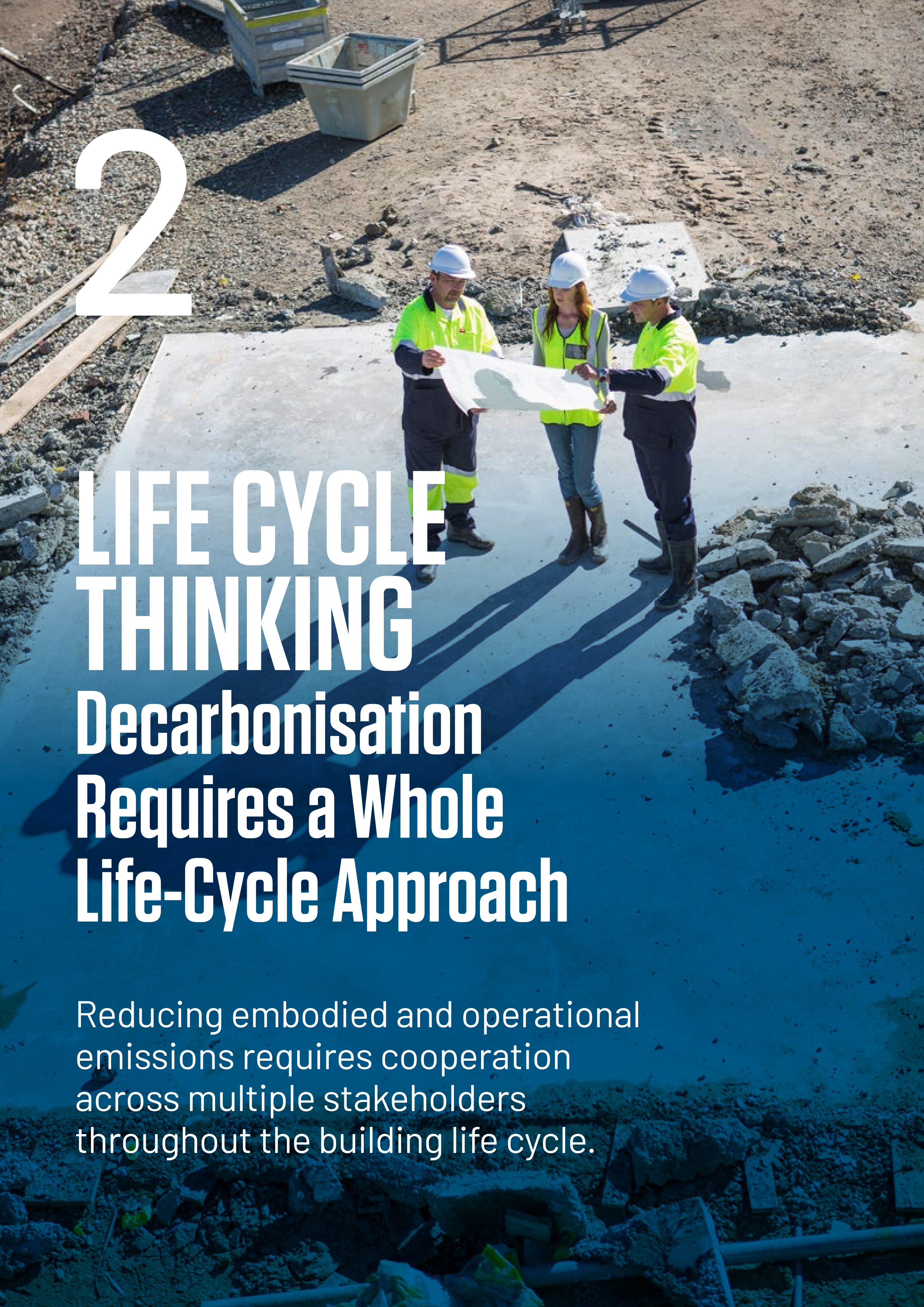
7 POLICY

Chapter 7 outlines key policy recommendations to illustrate these principles in real-world scenarios

8 CONCLUSION

Chapter 8 provides a brief conclusion and discussion.

Overall, the report shows that adopting a whole life-cycle strategy for decarbonizing the built environment process means: building less or building with less, incorporating circular materials strategies into new and existing buildings, designing buildings with lower lifetime operational emissions, and accelerating the use of low-carbon-intensity building materials.



2

LIFE CYCLE THINKING

Decarbonisation Requires a Whole Life-Cycle Approach

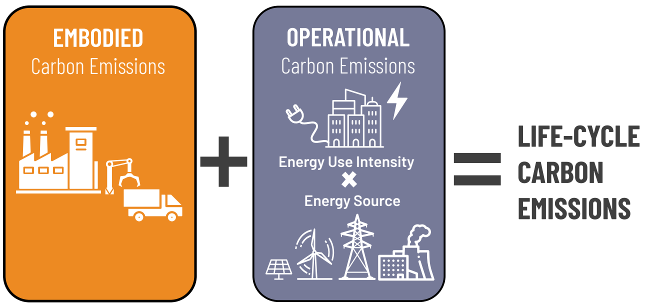
Reducing embodied and operational emissions requires cooperation across multiple stakeholders throughout the building life cycle.

2.1 Embodied versus Operational Carbon Emissions in Buildings

A building's carbon footprint reflects its combined embodied and operational carbon.

Transitioning to low-carbon built environments requires the design of material strategies that have multiple benefits and that take a "whole life-cycle" approach, in line with the principles of a circular economy. To appreciate the value of such an approach, it is important to first understand how and where most of the greenhouse gas emissions from the built environment are generated. These emissions are broadly split across two categories: embodied emissions and operational emissions (see **Figure 2.1**). Understanding the difference is key to decarbonizing the built environment sector:

2.1 Embodied and operational carbon emissions



A building's carbon footprint over its lifespan is the sum of its embodied plus operational emissions.

Adapted from Magwood *et al.* 2021.

- **Embodied emissions** are all the emissions associated with the construction (and deconstruction) of a building. They are generated during the extraction, manufacturing, transport and on-site construction of building materials (new buildings as well as renovations) and at "end-of-life" demolition, or, preferably, re-use for new buildings (GlobalABC and UNEP 2021).
- **Operational emissions** are the emissions generated through the function and maintenance of the building. They are released while maintaining the building's indoor "comfort levels," including by heating, cooling, lighting and electrical appliances. The initial design choices for a building (such as the building materials used) as well as upgrading materials during renovations, have significant impacts on the amount of operational carbon and on opportunities for recycling.

Within the total share of emissions from building and construction (37 per cent), the majority (11 per cent) are indirect operational emissions from residential buildings (see Figure 1.1). However, at least 6 per cent are embodied emissions from the most commonly used building materials: concrete, steel and aluminium.

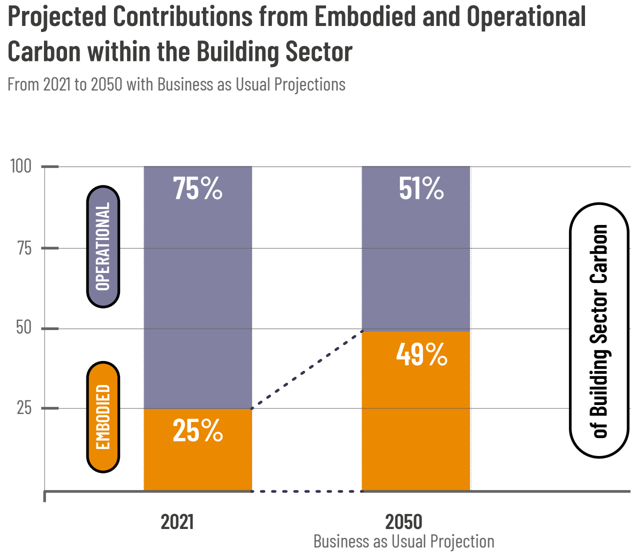
In recent years, considerable attention has been focused on how to reduce operational carbon in the built environment, as it currently contributes the lion's share of emissions from the sector (75 per cent) (see **Figure 2.2**). However, the share of embodied carbon of materials is projected to surge from 25 per cent to nearly half (49 per cent) by mid-century (OECD 2019). Meanwhile, the share of operational carbon will shrink as electricity grids increasingly transition to renewable energy and as building operations become more efficient (Architecture 2030 2022).

As a building's operational emissions shrink, the share of embodied emissions will grow.

Figure 2.3 illustrates how, over a building's lifespan, annual emissions from operational carbon (purple bars) will continue to decrease as the grid decarbonises by 2050. Meanwhile embodied carbon (orange bars) will remain high, if meaningful action is not taken to reduce it.

2.2 Projected contributions from embodied and operational carbon within the building sector

Under business as usual, embodied emissions will contribute nearly half of all building emissions by mid-century.



Adapted from Architecture 2030 2022.

The choice of materials impacts every aspect of a building's life-cycle carbon emissions.

The choice of construction materials impacts every aspect of a building's life-cycle emissions. Material selection has a huge impact on operational emissions because of the way it affects energy demand. Material choices can literally "change the (micro)climate" by contributing to the urban heat island effect (Narumi, Levinson and Shimoda 2021, see **Figure 2.4**). A material can either absorb the heat from the sun (as with concrete and brick), reflect solar heat gain (as with light-coloured surfaces) or transform solar energy (through on-site power generation and/or living materials such as green roofs).

The use of heat-absorbent materials such as concrete increases urban temperatures and the energy demand for cooling in buildings using mechanical air-conditioning (Davis and Gertler 2015; Deroubaix et al. 2021). Impervious surfaces such as concrete also cause excess water run-off and add to the carbon costs of pumping and treating stormwater. In certain climates, when designed properly, high-mass materials within buildings could support passive thermal effects and reduce requirements for heating and/or cooling (Pérez-Lombard, Ortiz and Pout 2008).

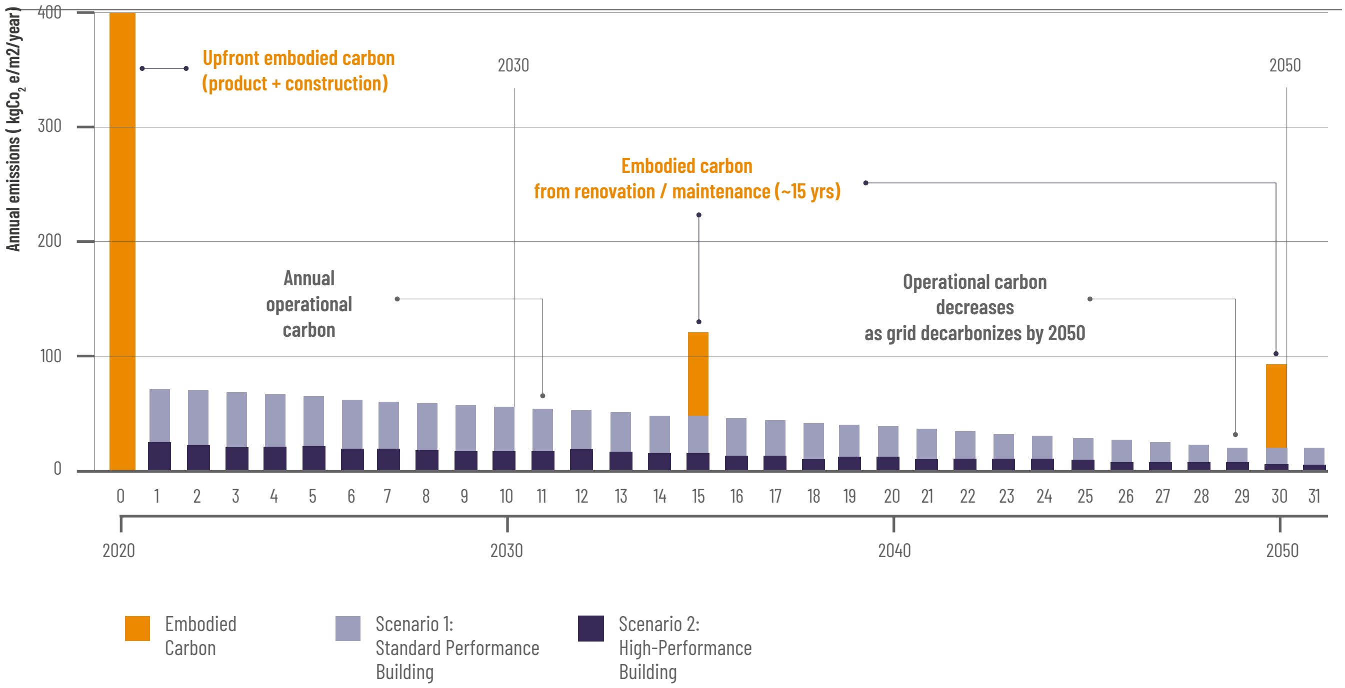
Given the huge impacts that building materials such as concrete have on both embodied and operational energy, the management of building material processes accounts for nearly one-fifth of global embodied carbon emissions, across the entire life cycle (OECD 2019).

2.2 Embodied Emissions from Extracting and Producing Building Materials

The share of emissions from producing building materials grew from 15% in 1995 to 23% in 2015.

Despite its massive contribution to climate change, the embodied carbon within materials has been under-addressed in decarbonisation strategies. In 2020, the International Resource Panel (IRP) highlighted the enormous potential to reduce emissions through strategies that increase the efficiency of material use in residential buildings. In the G7 countries as well as China, strategies such as the use of recycled materials could reduce emissions in the material cycle of residential buildings by 80 to 100 per cent by 2050 (IRP 2020). In India, the reductions could reach 50-70 per cent (IRP 2020).

2.3 Embodied and operational carbon emissions over the building lifespan



Operational carbon will continue to decrease with grid decarbonisation, while embodied carbon is set to remain high without meaningful action.

Adapted from Carbon Leadership Forum 2020.

The production phase of building materials is the main contributor to embodied carbon in buildings. With the surging demand for materials, the share of greenhouse gas emissions from producing building materials grew from 15 per cent in 1995 to 23 per cent in 2015 (IRP 2020). Historically, smaller buildings were made with local, lower-carbon materials (such as earth masonry), but these are increasingly being replaced by larger, carbon-intensive concrete and steel structures.

Many of the most commonly used construction materials today rely on energy-intensive, mineral-based extractive processes, and their emissions are set to increase (see **Figure 2.5**). In addition to climate impacts, these extractive processes can have deleterious social and environmental impacts across the material life cycle, such as biodiversity loss, high water consumption, water contamination and risk of forced labour.

The cement industry accounts for 7% of global CO_2 emissions.

- The production of cement and steel for construction accounts for more than 11 per cent of global and process-related carbon emissions (GlobalABC, IEA and UNEP 2019).
- Embodied emissions from the iron and steel industry comprise around 7 per cent of global greenhouse gas emissions and 11 per cent of global carbon dioxide (CO_2) emissions (Hasanbeigi 2021).
- The cement industry accounts for another 7 per cent of global greenhouse gas emissions, generated during the production and implementation of concrete structures (Hasanbeigi 2021; Miller et al. 2021).

2.3 Embodied Emissions: From End-of-Life to Re-Use and Recycling

To reduce embodied carbon, retrofitting and re-using buildings is preferable to demolition and building new.

At the "end-of-life" phase of buildings, any materials that are not recycled contribute substantially to rapidly growing waste production. To avoid this waste challenge – as well as the need to extract, process and transport new raw materials – retrofitting (to improve energy efficiency) and re-using buildings can be preferable to demolition and building new. The longer a building and its elements last, the less embodied carbon is expended (Historic England 2019). The average lifetime of buildings of all types currently ranges from around 30 years in China and India (Liu, Bangs and Müller 2013; Pauliuk et al. 2013; Hong et al. 2016) to 80 years in the United States of America (Müller et al. 2006; Kapur et al. 2008). Extending building lifetimes would create significant opportunities to reduce aggregate embodied carbon.

2.4 Impact of material selection on urban surface temperatures and the urban heat island effect

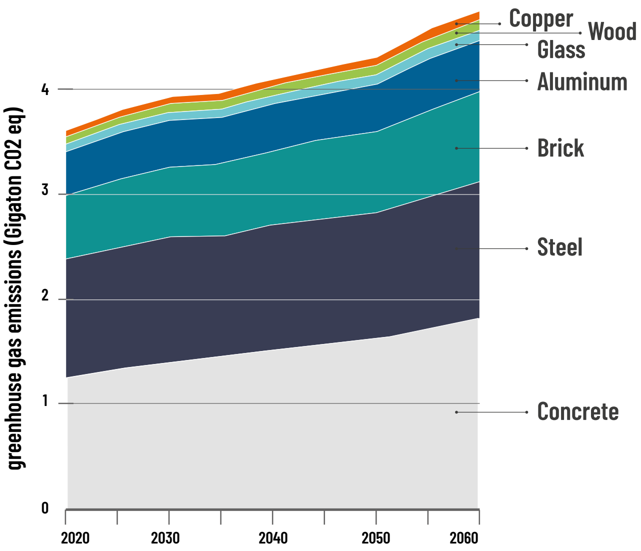
Building materials literally "change the climate" and are directly responsible for rising temperatures in urban areas.

A comparison of the surface temperatures from conventional roof materials versus green roofs, indicating dark purple (coolest), and yellow (hottest) roofs, showing that vegetated surfaces significantly decrease temperatures compared to asphalt. Source: U.S. Environmental Protection Agency 2017.

In the circular economy, the material waste from buildings is "designed out".

Applied to the built environment sector, the so-called circular economy envisions a future where the material waste related to buildings is "designed out." This is achieved by keeping

2.5 Projected greenhouse gas emissions from building materials in a business-as-usual scenario to 2060



Emissions from concrete, steel, brick, aluminium, glass, wood and copper are all set to increase substantially.

Source: Zhong *et al.* 2021.

construction materials in use and extending the life of a building for as long as possible (Haas et al. 2015). The re-use and recovery of materials is essential towards achieving circular production and use of building materials. The most carbon savings at a building's end-of-life comes from re-use: the re-use of a building, then reusing components, then reusing materials. By comparison, recycling and reprocessing of materials have lower decarbonisation benefits. Another path towards circularity is improving the efficiency of materials to enable better operating performance of buildings (see chapter 3).

2.4 Implementing a Whole Life-Cycle Approach to Building Materials

A whole life-cycle approach is necessary to enable multi-stakeholder engagement and cross-industry cooperation.

The built environment process involves energy, material and information flows at each of its life-cycle phases, from initial material extraction to final dismantling. The typical approach to the design and construction of buildings is linear, where at each phase of the life cycle the embodied carbon of a building accumulates. This increase in embodied carbon results from the use of energy and materials to: 1) source and extract building materials, 2) manufacture the materials, 3) construct the building structure from the materials, and 4) maintain the building during its service life. Hence, with each life-cycle phase there typically is a carbon investment. Although there are now agreed upon standards for reporting emissions (see **Figure 2.6**), it is often very difficult to accuratley estimate carbon footpinrts due to the insufficient data and/or knowledge of all contributing factors, which are complex, including natural ones. Therefore, there is still much development that needs to take place in tools and methods to support the production of reliable data across the board.

Increasingly, industry leaders are promoting a fundamental shift towards a circular, "whole life-cycle" approach to guide strategies to reduce both the embodied and operational carbon associated with building materials. (See tools in chapter 6.) A whole life-cycle approach is very different from a linear approach. It requires stakeholders to cooperate towards consideration of the environmental impacts of material choices before the materials are even extracted, and then at each subsequent phase of the building life cycle. This means thinking about not just how buildings are constructed, but also how the choice of materials affects the amount of heating or cooling needed, and how, at the end of their use, these materials can provide a "bank" of resources to then be re-used for another building's life cycle.

Looking at the building process from a whole life-cycle point of view means considering all the carbon costs of material choices, from the impact of material extraction on ecosystems to the environmental effects of production, construction, maintenance and demolition (see **Figure 2.7**). "Whole life-cycle emissions" are a combined measure of the embodied emissions in building materials and the operational emissions from a building's energy use and energy-source emissions (Magwood et al. 2021). By making assessments and decisions about carbon impacts over the course of the entire building life cycle, we can allow for choices that optimise for carbon efficiency between both embodied and operational carbon.

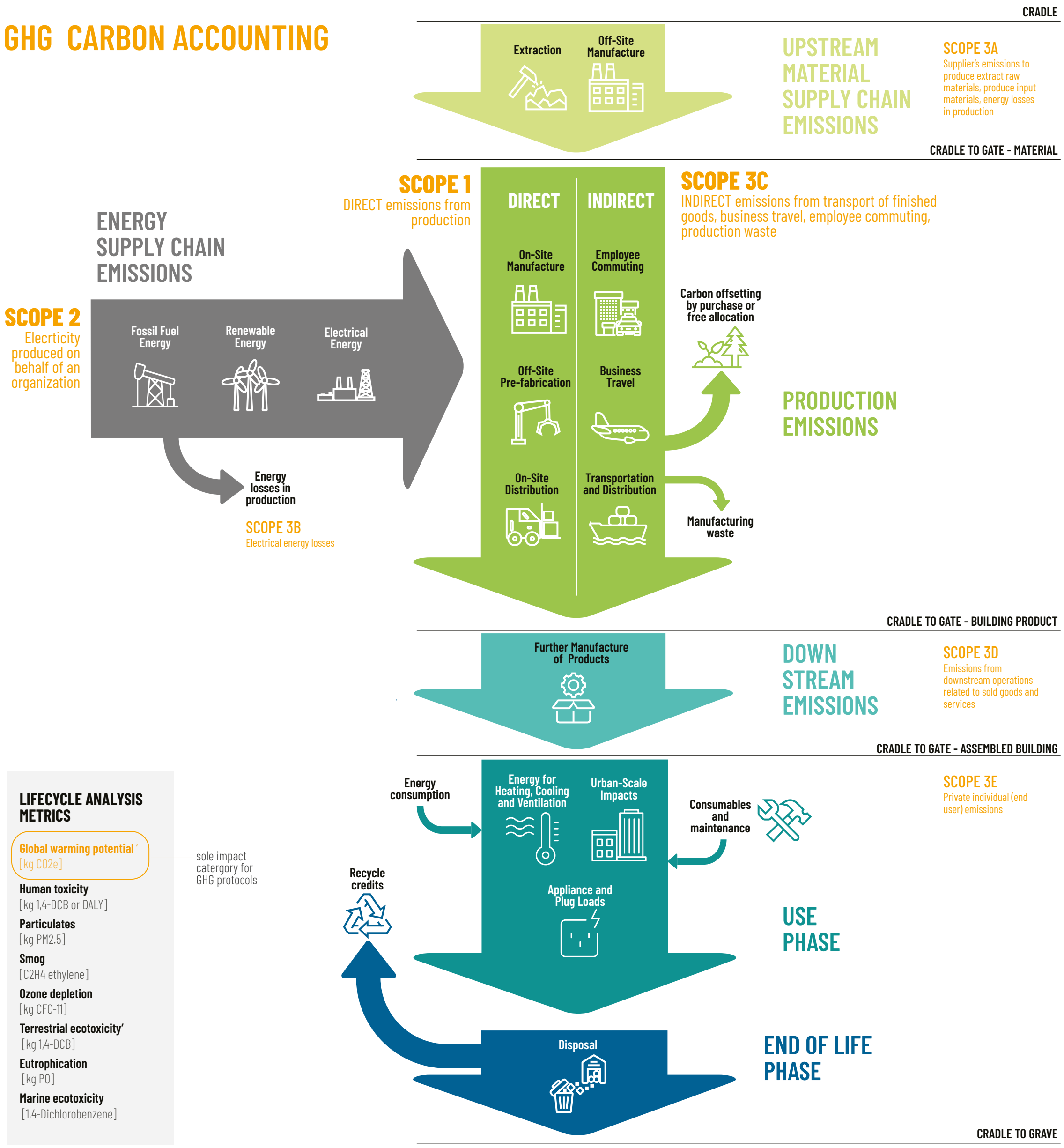
The whole life-cycle approach supports the deployment of a circular economy by enabling cooperation across stakeholders.

The whole life-cycle approach supports the deployment of a circular economy by enabling cooperation across stakeholders. If a new building's materials can be sourced from recycled materials at the beginning of its life – or, conversely, if a building's materials can be recycled at the end of its life – this will mitigate its embodied emissions and thus its total emissions over its lifespan. The main strategies for decarbonisation across a building's life cycle – from design to operations to end-of-use – must inter-relate for prime optimisation. The key to achieving whole life-cycle thinking is to ensure that the right decisions are made early in the design process to determine the carbon impact over a building's lifespan and

THE FIRST STEP WAS DEVELOPING A SYSTEM FOR COUNTING CARBON EMISSIONS NEXT WE NEED GLOBAL COOPERATION TOWARDS VERIFIABLE DATA ALONG THE SUPPLY CHAINS

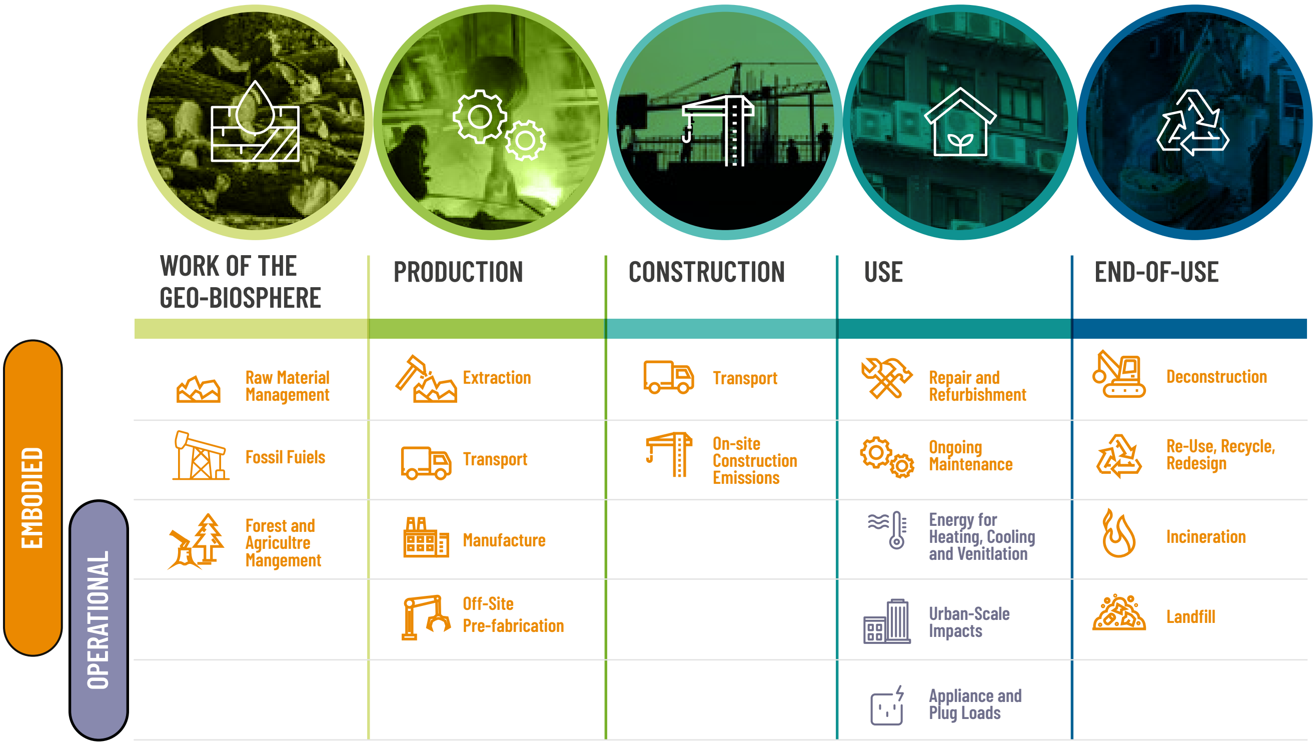
Figure 2.6 Scope 1, 2, and 3 carbon accounting for a material product

Carbon accounting for a material product considers Scope 1, 2, and 3 emissions. Scope 1 emissions from the direct production of goods and services, Scope 2 emissions from the energy used for production, and Scope 3 from indirect costs, upstream and downstream emissions.



Source: Adapted from " Life cycle analysis and GHG carbon accounting," Pons, 2022.

2.7 Carbon impacts of materials across the whole building life cycle



Taking a "whole life-cycle" approach means considering all the carbon costs of material choices.

Note: Looking at the building process from a whole life-cycle point of view means considering all of the environmental and carbon impacts during a building's life cycle: from extraction to end-of-life. Adapted from CLF 2020.

end-of-life (see chapter 3). This is true not only at the building scale but also at the district level: material choices in urban design affect the wider ecosystems with which a building will interface (from land and water quality to the electric grid), as well as their relative impacts.

Whole life-cycle thinking requires being sensitive to the context, including local cultures and climates. Although a substantial shift to low-carbon building materials – such as recycled and earth- and bio-based materials – is technologically possible, it may be socially hard to implement, as many regions consider concrete and steel to be the "modern" materials of choice. Such a shift has tremendous potential due to growing experience with engineered timber and bamboo as substitutes for steel and concrete, and the ability to use components derived from forestry, agriculture and biomass by-products. Yet none of these improvements can scale impactfully without innovation and whole life-cycle coordination across producers, designers, builders and communities.

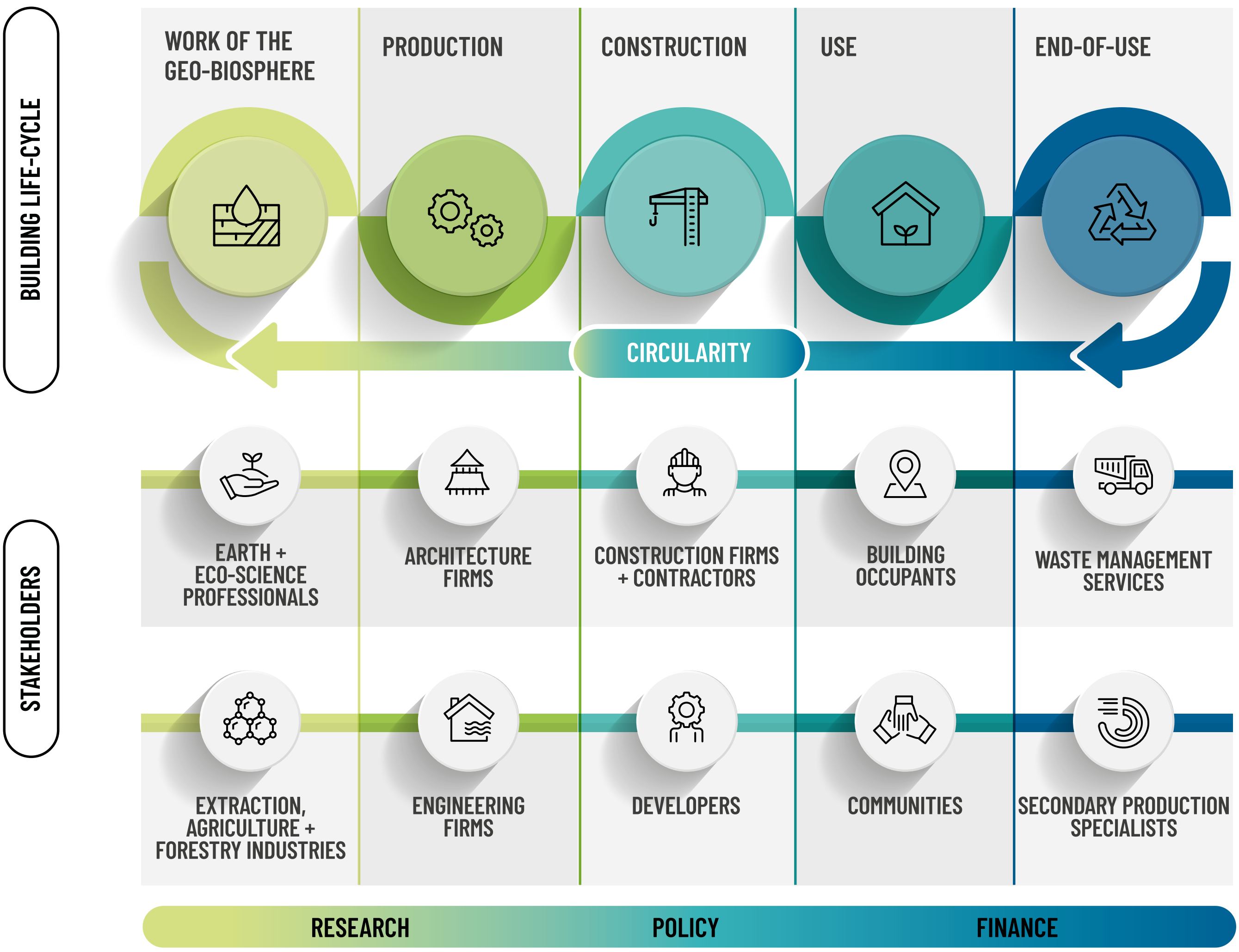
2.5 The Whole Life-Cycle Approach: Pathways for Decision-Makers

Assessing the carbon costs of built environment systems must include measuring the impacts on the productive capacity of global ecosystems.

Globally, strategies for decarbonizing buildings will differ greatly by region depending on local natural resources and the building stock, as well as on projected needs for the future. Patterns in material flow scenarios suggest that in developed countries, the priority is to renovate the existing and ageing building stock, while repurposing waste into "material banks." In developing countries, rapid urbanisation means a focus on new construction; in this context, the potential to transform economies by designing out waste in the early stages – from the district to the building scale – has great promise.

TRANSITIONING TO A CIRCULAR ECONOMY REQUIRES INCENTIVES FOR NEW MODELS OF COOPERATION ACROSS THE LIFECYCLE

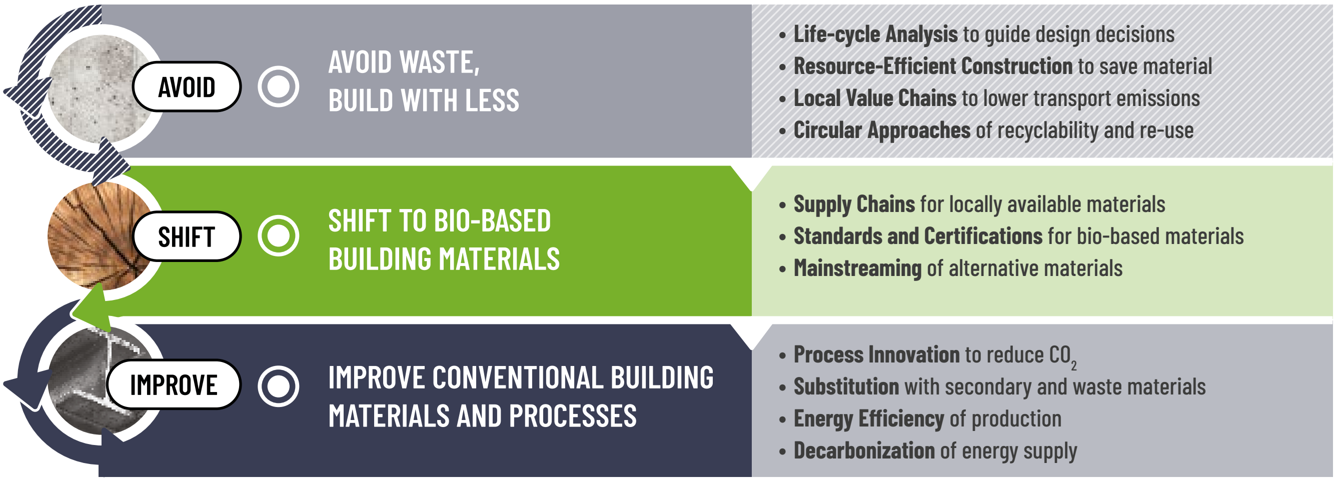
2.8 Key stakeholders whose participation is critical to the decarbonisation of buildings at different life phases



They include scientists; architecture, engineering and construction firms; building occupants; and waste management and recovery professionals.

Adapted from Keena and Dyson 2017; Keena et al. 2023.

2.9 Decarbonising buildings and construction through the Avoid-Shift-Improve approach



Adapted from PEEB 2021.

Because there is no one strategy to decarbonise materials, decision-makers must take cumulative measures across the lifespan of buildings. Active participation across stakeholders is central – everyone from earth science professionals; to architecture, engineering and construction firms; to building occupants and communities; to waste management professionals. Access to correct information is also key for data-driven policies, financial instruments and research incentives to support each phase of the building and material life cycle, and for each stakeholder group (see **Figure 2.7**).

2.6 Strategies Towards a Building Materials Revolution: "Avoid-Shift-Improve"

To decarbonise building materials by 2060, we must urgently support solutions across all major material types simultaneously.

The transition to sustainable, low-carbon materials will revolutionise the way we construct cities, infrastructure and buildings. To achieve a 40 per cent reduction in embodied carbon by 2030 – and completely decarbonise building materials by 2060 – we must immediately support viable solutions across all the major material types simultaneously.

Transitioning to a low-carbon future requires avoiding new raw material extraction of materials. If buildings are designed for circular disassembly and reassembly, they technically become material banks at the end-of-life. To reduce embodied emissions, non-renewable resources such as concrete and steel need to be obtained from recycled or reused sources wherever possible. This should be complemented by a shift towards renewable, bio-based products if practical. In sum, a revolution in building materials requires: 1) dramatically reducing emissions from conventional (non-renewable) building materials, and 2) accelerating growth in alternative (renewable) materials.

Based on this understanding, the actions needed to reduce embodied carbon across the whole life cycle of buildings and construction can be clustered into three main strategies, using the "Avoid-Shift-Improve" framework (Programme for Energy Efficiency in Buildings [PEEB] 2021a) (see **Figure 2.8**):

- **AVOID waste, build with less and improve circularity** through better design and decision-making. This includes using resource-efficient design, extending the lifetime of buildings, and "doing more with less" through holistic design and circular economy strategies that design out carbon from the start. It also means prioritising the use of recycled, secondary and reused materials, which requires design for disassembly and the re-use of buildings and components. (See chapter 3.)
- **SHIFT to renewable, bio-based building materials** to reduce demand for primary extraction. This includes greater use of agriculture and forestry by-products. Rather than relying on virgin forest for materials, it requires using wood and timber harvested from lands that were once used for agriculture and implementing sustainable management and afforestation practices. (See chapter 4.)
- **IMPROVE conventional building materials** hrough decarbonisation efforts, including through energy and material efficiency and the use of renewable energy in production. Materials made from primary sources should be produced using best available technologies and electrified processes, and end-of-use recycling and re-use should be prioritised. (See chapter 4.)

Box 2.1 provides an overview of how decision-makers can adopt a whole life-cycle approach and use these three strategies to transition building materials to a low-carbon future.

BOX 2.1

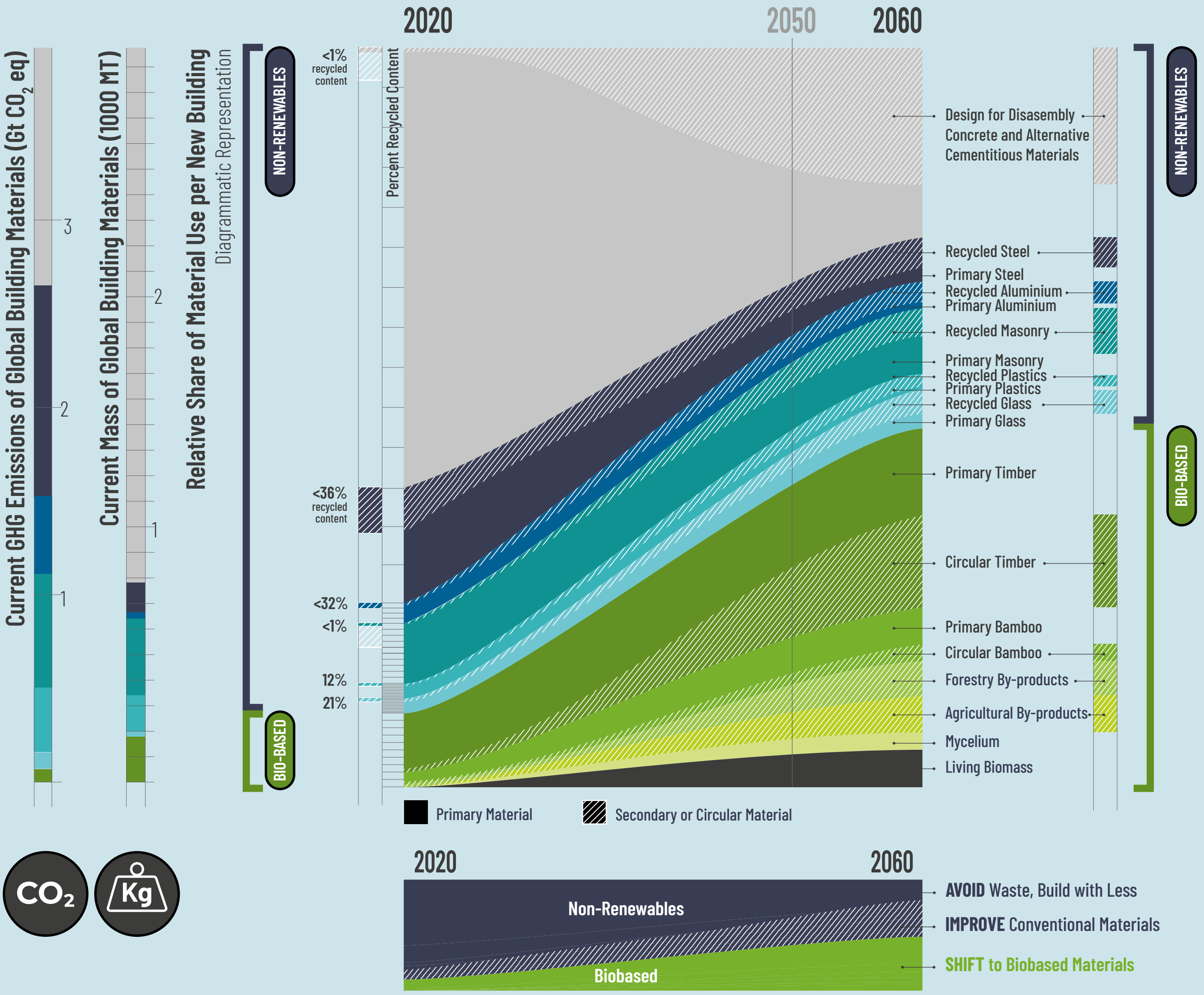
TRANSITIONING BUILDING MATERIALS TO A LOW-CARBON FUTURE

Due to the integration of many materials in building systems, it is essential to support efforts to reduce carbon emissions across all building materials.

Across all climate types, buildings will continue to rely on a broad range of both conventional and emerging material streams. However, moving towards a low-carbon future requires a cumulative change in how building materials are used and sourced, across the full spectrum of materials. It requires holistic application of the "Avoid-Shift-Improve" strategies promoted in this report to prevent overuse of extracted raw materials and to facilitate the shift from non-renewable to renewable and secondary sources.

Figure 2.10 shows how these actions would change the type of building materials used and their sourcing. A consistently adopted whole life-cycle approach coupled with the decarbonisation of primary emitters such as concrete/cement and steel would dramatically reduce embodied emissions across new and existing buildings.

2.10 Transitioning building materials to a low-carbon future



Decarbonisation requires a change in use across all building materials.

Source: Ciardullo, Reck and Dyson 2023. Current GHG Emissions: Zhong et al. 2021; OECD 2022a. Material mass and recycling rates from: Miatto et al. 2017 (cement); Cullen, Allwood and Bambach 2012, Reck 2022 (steel); International Aluminium Institute [IAI] 2020 (aluminium); Westbroek et al. 2021 (glass); Miatto et al. 2017, Miatto et al. 2022 (masonry); DI et al 2021, Geyer, Jambeck and Law 2017 (plastics); Food and Agriculture Organisation of the United Nations [FAO] 2020 (timber).

3

AVOID Waste, Build (with) Less and Improve Circularity

There are opportunities for circular design, recycling and re-use at each phase in the building life cycle.

3.1 Circular Design Tools and Strategies for Planning and Decision-Making

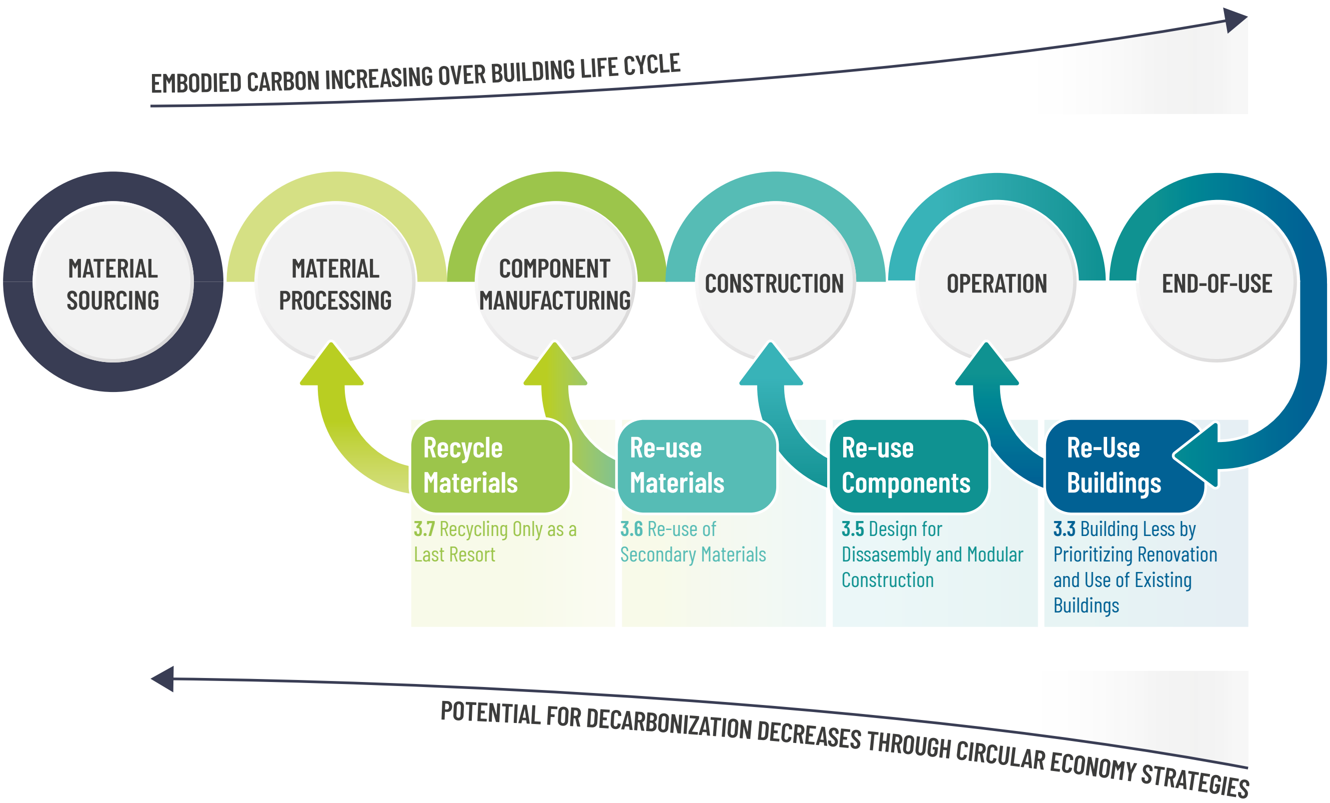
How we design our buildings is key to achieving a circular economy.

A circular economy for the built environment is rooted in design and decision-making (Keena and Rondinel-Oviedo 2022). Design decision-making during each phase of a building's life cycle offers opportunities to reduce embodied carbon (see **Figure 3.1**). Key interrelated circular design tools and strategies include:

- upstream design choices (for example deciding on what to build, form, layout, materials etc.), including building (with) less and building smarter;
- selecting building materials and elements that have lower embodied carbon because they are either recycled/re-used or are inherently lower-carbon; and
- end-of-use strategies to avoid waste and enable the re-use and recycling of materials and components.

These strategies must be considered in tandem. For example, re-using materials as much as possible is a good start, but there is a growing gap between the available supply of and demand for recycled materials (see chapter 5). Therefore, a next good step might be to replace high-carbon materials with low-carbon renewable materials, such as bio-based materials. However, it remains unclear how the scaling of biomaterials, such as wood and bamboo, will impact the ability of regional ecosystems to sequester carbon. Bio-based materials are low carbon in their processing and use, but this must be accompanied by sustainable forestry and farming practices (Keena, Duwyn and Dyson 2022) (see chapter 4).

3.1 Opportunities to reduce carbon at each phase of the building life cycle



Decarbonisation requires a change in use across all building materials.

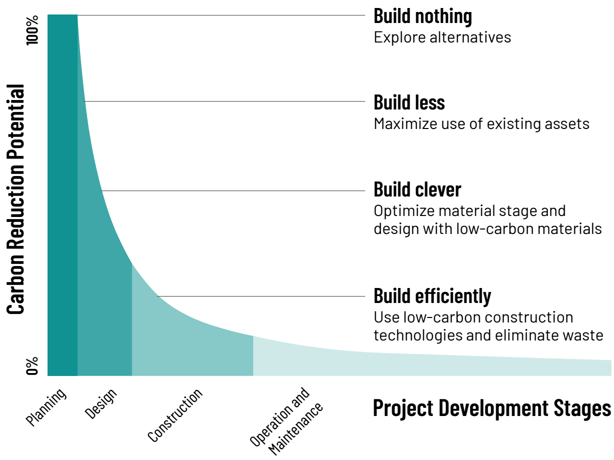
Source: Keena, Rondinel-Oviedo and Acevedo De los Ríos 2023, adapted from Akbarnezhad and Xiao 2017.

3.2 Upstream Design Choices Are Key to Tackling Carbon Early

Early design choices have repercussions on the ability to reuse or recycle materials later on.

The potential to reduce and avoid embodied carbon is greatest during the early planning and design phases (see Figure 3.2) (HM Treasury 2013; World Green Building Council 2019; PEEB 2021a). At this early planning stage, taking a whole life-cycle approach to project future low-carbon scenarios is key. Circular design strategies focus on how upstream design choices impact embodied carbon throughout the life cycle. Early design choices have repercussions on the ability to reuse or recycle materials later on

3.2 Opportunities to reduce carbon in each stage of project development



The potential to avoid embodied carbon is greatest during the planning and design phases.

Source: HM Treasury 2013; World Green Building Council 2019.

Designing Out Waste and Emissions from the Start

The first question to ask is whether anything new needs to be built at all.

A circular economy approach aims to design out waste. The priority is to keep materials and buildings in use as long as possible and to ensure that they are re-used rather than turned to waste. Many opportunities exist in both new construction and renovation to design out waste, avoid embodied carbon and plan ahead by incorporating strategies earlier in the life cycle.

The first question to ask is whether anything new needs to be built at all. Alternatives to new construction should be explored. For existing buildings, circular renovation and retrofit strategies, such as extending the life of the building, coupled with advanced recovery and recycling, are key to achieving low-carbon outcomes. Where new construction is a necessity, designs should aim to maximise building lifespans and to promote resource and material efficiency, thereby reducing the embodied carbon expended. During this early phase, embodied carbon emissions can be avoided by eliminating new materials, such as by increasing the use of existing assets and promoting adaptive re-use.

Importantly, upstream design choices have repercussions for potential end-of-life strategies. These include choices about building morphology, material selection, and construction assemblies (which affect both embodied and operational emissions) as well as the potential for disassembly at end-of-life. Considering the end-of-life during these early phases can result in the avoidance of waste and associated carbon emissions later in the building life.

This underscores the importance of using evidence-based decision-making in the selection of materials, with regard to embodied emissions, in this phase. One key way to promote evidence-based design is by enacting performance-based building standards and undertaking regulatory reforms to allow for performance-based rather than prescriptive standards, to enable the use of alternative low-carbon materials and construction techniques. (See chapter 6 for more on tools.)

Circularity Strategies Are Context Specific

On the path towards decarbonisation, different decisions will need to be made depending on whether there is a need for new construction, or for renovating existing buildings. New construction and renovation are happening globally (UNEP and IEA 2017). However, if the current linear approach to renovation and new building construction continues, it will exacerbate climate change.

Decarbonisation strategies will differ by region because of variations in the available building stock. Material flow scenarios suggest that in developed countries, the priority is to renovate existing and ageing building stock and to repurpose waste into material "banks." In developing countries, rapid urbanisation means a focus on new construction; in this context, designing out waste in the early stages is promising. However, in both contexts, designing buildings that are easily reused, repaired or recycled at their end-of-life is vital if we are to shift from a linear to a circular economy.

3.3 Building Less by Prioritising Renovation and Use of Existing Buildings

In a circular economy, extending a building's life is the most valuable and least wasteful option.

The best way to reduce the embodied emissions of building materials is to avoid major new construction. In a circular economy, where waste is avoided, extending a building's life is the most valuable and least wasteful option, whereas downcycling is the least valuable option (Figure 3.1). Thus, planners should favour the refurbishment and upgrading of existing buildings – using reused materials when possible – to reduce the need for non-renewable material extraction. The lifetimes of buildings can be extended by incentivizing renovations and retrofits over demolition.

Renovation Will Skyrocket in the Coming Decades and Can Result in Much Lower Emissions

Renovations generate around 50-75% fewer emissions than new construction.

In the coming decades, large numbers of existing buildings will require repairs and reparations. By 2030, there is expected to be a sharp increase in the number of concrete structures becoming overburdened and in need of building system repairs (such as structure and finishing) (Vilches, Garcia-Martinez and Sanchez-Montañes 2017). The value of the global concrete restoration market is set to increase at a compound annual growth rate of around 6 per cent by 2030, to reach nearly $26.4 million (ibid.). This growth is projected to be greatest in North America, where many mid-century structures are experiencing premature deterioration due mainly to poor building quality, improper design and a failure to make timely repairs.

Decisions at an early phase to use less materials by re-using buildings or their components – especially retaining foundations and structural systems – results in avoided demolition and waste, and less embodied carbon. Renovating existing buildings generates around 50-75 per cent fewer greenhouse gas emissions than new construction, because it typically involves re-using the building structure and envelope, which make up most of a building's carbon-intensive processes and materials (e.g., concrete, brick, steel and aluminium) (Strain 2017).

> Prioritise the Use of Low-Carbon Materials in Retrofits

The selection of materials and systems is critical towards creating a low-carbon building. Engineered bio-based materials, such as cross-laminated timber and bamboo, offer the potential to replace concrete and steel components, particularly for the widespread re-purposing of older commercial buildings, where new floors are added to supplement housing units. Swapping a concrete-based exterior wall system with

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a bio-based structure such as timber or bamboo could greatly reduce both the upfront embodied carbon and the ongoing operational emissions associated with heating and cooling systems. Carbon emissions from renovations can be further reduced by avoiding the replacement of high-carbon materials such as carpeting and ceiling tiles, and instead simply polishing the sub-flooring and ceiling structure as the interior finish.

> Repurpose Waste to New Functions On-site or Nearby

Repurposing waste materials into new functions on-site or for nearby use can save carbon.

Extending the lifespans of existing buildings and re-using existing components helps to avoid the loss of "waste" materials to landfills. Because renovation projects are undertaken at the building site, when older materials are torn out they can generate up to 20-30 times as much on-site waste as new construction (Strain 2017). Therefore, carbon savings can be achieved by repurposing waste materials into new functions on-site or for use in nearby construction in another building life cycle. These methods are already widespread in informal and semi-formal housing throughout the world, and much could be learned from those practices for the formal sector as well.

> Prioritise Socio-cultural Connections to Buildings to Incentivise Their Continued Use

Buildings that last are ones that people are personally attached to.

The lifespan of buildings and infrastructure is not determined solely by physical durability, but also by social, cultural and economic factors (Cao et al. 2021). Buildings that last are ones that people are personally attached to. Emotional and cultural factors can incentivise property owners and especially third-party developers to choose durable materials over those with the lowest initial cost. Materials are fundamental in establishing durable value over time, and the impact that materials have on occupants' connection to a place transcends mere functional use.

3.4 Focusing on End-of-Use, Not End-of-Life, to Avoid Landfill

Transitioning from end-of-life to end-of-use promotes a circular economy approach.

Traditionally, end-of-life is the phase of a product's life cycle where the end treatment or waste management occurs. It is the final phase in the linear economy of "take, make, waste." Three potential end-of-life strategies for dealing with a building's materials and components include landfill, selective deconstruction and recycling.

Avoiding Landfill and Embracing Material Reuse

At the end-of-life of buildings, the most common waste management strategy is demolition followed by disposal of materials in a landfill. However, this results in a loss of the invested carbon accumulated over the building's lifespan, as well as in additional carbon emissions from demolition, transport and the landfill itself (Akbarnezhad and Xiao 2017; Di Maria, Eyckmans and Van Acker 2018). Of the roughly 100 billion tons of construction, renovation and demolition waste generated annually, around 35 per cent is sent to landfill on average (Chen, Feng et al. 2022) (see **Annex 1**).

Diversion and innovative management can greatly reduce waste (Iyer-Raniga and Huovila 2020). For example, much of this disposed material could instead be recuperated and recycled, turning demolition sites into material banks for new buildings. However, greater research and development into designing recyclable components needs to be supported, and building codes need to require compliance.

A transition to a circular economy warrants transitioning from an "end-of-life" perspective to "end-of-use." At the end-of-use stage, there is the potential to preserve (or store) the invested embodied carbon in a future housing cycle. A circular economy strives to improve resource efficiency, primarily by closing the resource loop (Haas et al. 2015). Within the building sector, this involves reducing the use of virgin raw materials at the manufacturing phase and substituting it with secondary materials that are in their second or third life cycle – and, consequently, eliminating waste at the end-of-use phase.

Selective Deconstruction to Avoid Embodied Emissions

Selective deconstruction involves dismantling a building rather than demolishing it.

A potentially lower-carbon approach to the end-of-use of a building is selective deconstruction, which involves dismantling the structure rather than demolishing it. Practices of re-use, repair and recycling allow for retaining the value of the building components and materials. Research indicates that selective deconstruction can offer large carbon savings over landfill. In a study in Belgium, it led to a 59 per cent decrease in greenhouse gas emissions per capita compared to landfill, whereas implementing recycling and downcycling practices alone led to a 36 per cent decrease in emissions (Di Maria, Eyckmans and Van Acker 2018).

Similarly, a study comparing two very different housing sectors globally – in Lima, Peru and Montréal, Canada – found that avoiding waste by diverting construction, renovation and demolition materials from landfill can greatly reduce emissions. The study found that a selective deconstruction approach of re-use and recycling had the greatest decarbonisation potential compared to landfill, leading to emission reductions of 70 per cent in Lima and 63 per cent in Montréal (see **Box 3.1**).

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BOX 3.1

LIMA AND MONTRÉAL: UNDERSTANDING THE DECARBONISATION POTENTIAL OF CIRCULAR END-OF-USE STRATEGIES

Re-use and recycling strategies can reduce emissions in residential construction by up to 70%.

Circular end-of-use strategies can reduce the life-cycle greenhouse gas emissions associated with residential buildings in Lima, Peru by 70 per cent and in Montréal, Canada by 63 per cent. These strategies could: 1) reduce the demand for virgin construction materials; 2) make secondary materials available, thereby reducing the need to produce virgin materials; and 3) increase the re-use of materials via selective deconstruction to reduce the emissions from demolition and landfill.

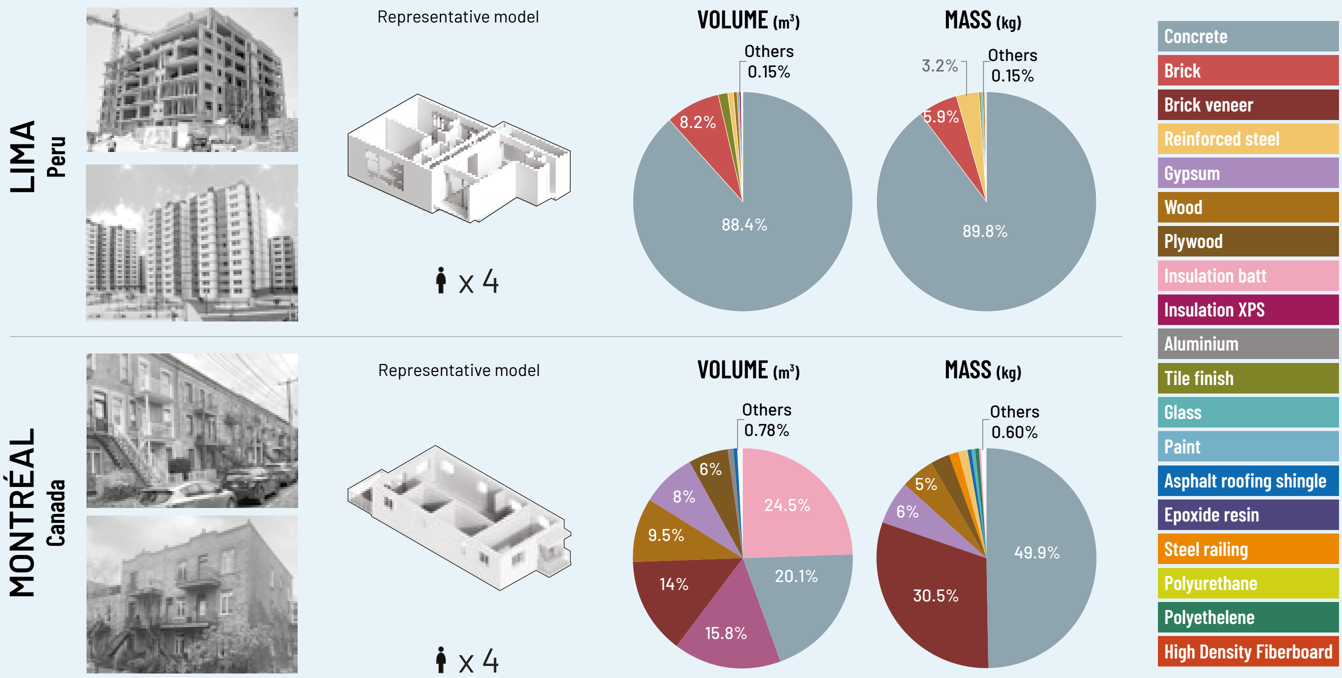
Building material use in Lima: a housing boom with growing reliance on imports of high-carbon materials

In Peru, 1.8 million homes are due to be built by 2030 (National Statistics and Information Technology Institute 2017). The main construction materials used for multi-family housing projects in Lima, as of 2019, are shown in **Figure 3.3**, with concrete being dominant (Peruvian Chamber of Construction 2020). Although many materials are manufactured locally, there is a trend towards importing high-embodied-carbon raw materials. This includes 51 per cent of steel scrap (Ministry of Foreign Trade and Tourism 2018); 100 per cent of aluminium and floated glass (Lopez 2022); and 4.7 per cent of cement (Vázquez-Row et al. 2019). Up to 82 per cent of building construction waste in Lima is dumped at informal, illegal sites (Rondinel-Oviedo 2021), with minimal recycling.

Building material use in Montréal: Rising demand for renovations and a large share of construction waste

In 2021, Statistics Canada reported that 59 per cent of homeowners in Montréal planned a home renovation. Apartments make up 58 per cent of the city's dwellings, with buildings of less than five storeys being the most common (Statistics Canada 2017; Statistics Canada 2019). The material breakdown of Montréal's low-rise apartments is shown in **Figure 3.3** (Keena, Rondinel-Oviedo and Demaël 2022). Across Canada, construction, renovation and demolition waste represents 20-30 per cent of all solid waste (Yeheyis et al. 2013).

3.3 Representative housing in Lima and Montréal and typical materials used, by mass and volume, 2019



Whereas concrete dominates in Lima's buildings, material use in Montréal is more diverse.

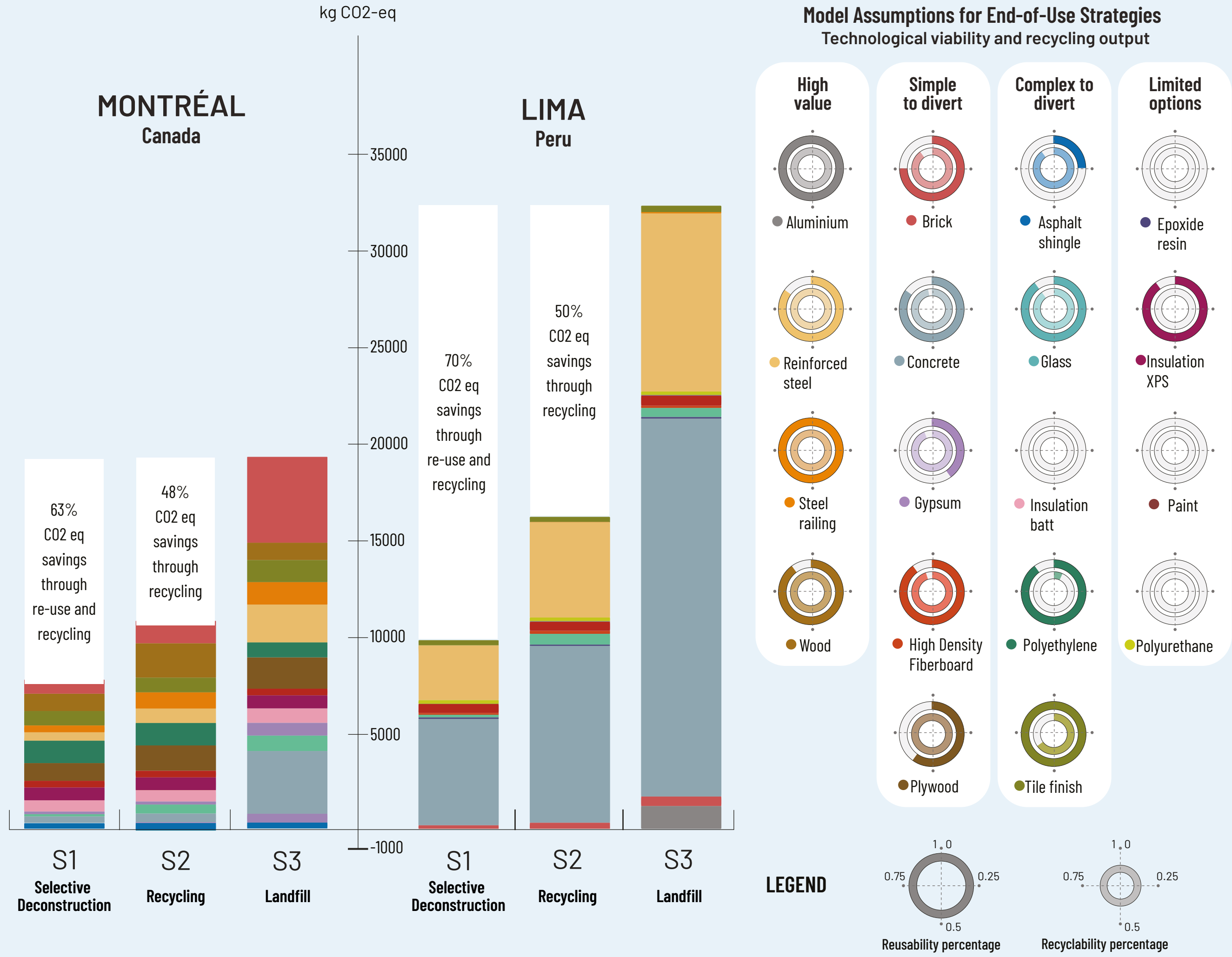
Source: Keena et al. 2023.

The potential of end-of-use strategies to reduce emissions from residential buildings
Material management strategies employed at the end-of-use phase of buildings offer opportunities for carbon savings. Based on representative housing models (see Figure 3.3), a recent study focused on three specific end-of-use strategies for Lima and Montréal:

- 1 – Selective Deconstruction, dominated by re-use but also including recycling
- 2 – 100% Recycling
- 3 – 100% Landfill

The study found that selective deconstruction (re-use and recycling) had the greatest decarbonisation potential, leading to reductions in greenhouse gas emissions of 70 per cent in Lima and 63 per cent in Montréal, compared to landfill (see Figure 3.4). Meanwhile, recycling alone reduced emissions 50 per cent in Lima and 48 per cent in Montréal. This illustrates that circular end-of-use strategies of material reuse and recycling offer a much lower-carbon approach. The emission declines are due mainly to the avoidance of landfill and to the recovery of material for reuse. Re-use and recycling lead to a reduction in the primary energy and raw materials needed to process virgin materials into new materials during the manufacturing phase.

3.4 Carbon impacts of different end-of-use strategies in Lima and Montréal



Re-use and recycling had the greatest potential for decarbonising housing, compared to landfill.

Note: Scenario 1 (S1) = Selective Deconstruction (Lima: 84% re-use, 15% recycle; Montréal: 77% re-use, 21% recycle), Scenario 2 (S2) = Recycling (Lima: 96% recycling, Montréal: 94% recycling), and Scenario 3 (S3) = 100% Landfill. The legend shows assumptions on the levels of re-use and recycling viability.
Source: Keena et al. 2023

3.5 Design for Disassembly and Modular Construction

Facilitating Future Material and Component Recovery

Design-for-disassembly strategies can result in 10-50% reductions in life-cycle impacts.

"Design for disassembly" and modular construction facilitate selective deconstruction. These methods can extend the longevity of building components and enable dismantling at the end-of-use. Because the value of these building elements is retained, they can easily be reused (Keena and Dyson 2020). Studies show that design-for-disassembly strategies can also result in 10-50 per cent reductions in greenhouse gas emissions compared to conventional construction (Keena et al. 2022). However, challenges can arise in earthquake-prone regions, where secure building joints are needed. To overcome such challenges, governments can support research for new design-for-disassembly systems and recovery methods, such as the re-use of reinforced concrete as a structural element with the need to address seismic resistance.

Digitalization to Support Design for Disassembly

Digitalization to support prefabrication and modular construction can reduce waste by 23-100%.

Digitalisation – such as three-dimensional building information model technologies – can help with the design and fabrication of the complex connecting components required in design for disassembly. It can also help minimise material waste during construction by resolving issues before materials land at a worksite. Digitalisation to support prefabrication and modular construction has been proven to reduce waste by 23-100 per cent (Jaillon, Poon and Chiang 2009; Lu and Yuan 2013; Chen, Msigwa et al. 2022).

Building information modelling is a digital solution that can be applied to all building types. However, for smaller and less-complex buildings, it may be simpler to use a building passport. A building passport is a whole life-cycle repository of building information – a digital description of a building. It covers a building's administrative documentation as well as data regarding its site and location, its technical and functional characteristics, and its environmental, social and financial performance (GlobalABC and UNEP 2021). Building passports can play a role by creating a data repository that tracks material changes, maintenance and repair that have occurred in a building over time.

3.6 (Re-)Use of Secondary Materials

Government incentives can encourage the re-use marketplace and widespread adoption of secondary materials.

Secondary materials such as scrap or residuals from construction processes are currently massive sources of waste and have great potential for integration into building structures. For secondary materials to compete strongly in the construction materials marketplace, technical, operational, social, cultural, regulatory and economic limitations need to be overcome (Knoth, Fufa and Seilskjær 2022). Policymaking is key in helping to overcome limitations such as the lack of a regulatory framework. Government incentives can encourage both the re-use marketplace as well as the widespread adoption of secondary materials and selective deconstruction practices.

Funding Is Needed to Address Technical Challenges

From a design perspective, the weight and dimension of an element or material can greatly influence its re-usability. Lighter and smaller materials and components, designed with flexible joints, will be more feasible to reuse. Funding mechanisms are needed to advance research and development to overcome technical limitations of re-use and recovery, such as material degradation, seismic and fire-proof specifications, and design for disassembly.

Research can also help tailor frameworks for re-use to different contexts. As was illustrated for Lima and Montréal (see Box 3.1), the carbon savings from end-of-use strategies can differ across regions depending on the technical specificities. In regions where reinforced concrete is commonly used, the re-use of structural elements is less viable. For earthquake-prone regions, the design of re-usable structural elements will need to address the seismic resistance of materials. In contrast, in regions that use lighter materials, such as wood, the potential for re-usability is higher. However, most secondary lightweight wood is not reused or recycled today but is used mostly for energy recovery (see chapter 4).

Education Is Required to Increase Technical Knowledge and Social Acceptance

To increase technical knowledge exchange on the use of secondary materials, governments can support training, education and research on the practices and skills needed to conduct selective deconstruction (McClure and Bartuska 2007; Deplazes 2012; Rondinel-Oviedo and Schreier-Barreto 2019; Cruz Rios and Grau 2020; Hossain et al. 2020). From a socio-cultural perspective, specific messaging also needs to be developed to shift the mindset that secondary materials are of lesser value. Instead, it is important to convey the notion that these materials are desirable and to support their acceptance in the marketplace.

Policies Can Support Standards for Secondary Materials and Incentivise Markets

Markets are needed for re-usable products, with specialised contractors and re-use centres leading to new job opportunities

The development of assessment standards and certifications for secondary materials is key in assuring the safety and efficacy of re-use materials. This, in turn, can help promote selective deconstruction. Policies are needed to develop and regulate the government approval process for materials before they enter the marketplace. For instance, secondary materials must meet recognised material standards and certification regarding their composition and properties, and must also comply with building codes. Secondary materials must be assessed to ensure that they meet the same standards as virgin materials in order for legal limitations and social acceptance to be overcome.

Economic drivers for re-use can be as effective as legislation (King 2021). Financial incentives can support the creation of a re-use marketplace – new enterprises and specialised deconstruction contractors that allow for the careful dismantling of a building and for the storing, preparation and maintenance of secondary materials for resale. This includes establishing re-use centres that concentrate end-of-use materials in a "one-stop shop" (Forrest 2021), where elements with higher value can be resold before going to sorting facilities. By enabling circular economies in the building sector, new job opportunities can be provided.

3.7 Recycling Only as a Last Resort

Many regions have a lack of confidence in recycled products and face cultural resistance.

In a circular economy paradigm of "re-use, repair, recycle," where waste is eliminated, the practice of recycling or downcycling becomes a last resort, as it typically results in a product of lesser value. Although diverse recycling techniques have been well developed globally, many regions have not implemented recycling methods for construction, renovation and demolition waste due to various limitations. These include: a lack of confidence and reluctance in recycled products, cultural resistance, lack of certainty around the economic feasibility and viability of investing in advanced recycling methods, poor communication and coordination among parties, and insufficient policies and regulations (Jin et al. 2017). Illegal dumping is also an issue, particularly in many developing countries.

In the case of Lima, Peru, imported materials with high embodied carbon, such as steel and the cement used for concrete, make up around three-quarters of construction, renovation and demolition waste (Rondinel-Oviedo 2021). This is common across the developing world. However, much of this material could be recovered for reuse or recycling. Studies have shown specific examples where government incentives, awareness, and knowledge transfer, as well as legal and regulatory frameworks regarding recovery of these materials, have been effective (Liu, Bangs and Müller 2013).

Recycling and reuse reduce the need to import virgin materials and also help promote the local value chain. On-site sorting and processing of materials benefit re-use and recycling enterprises and make waste management more efficient. Additionally, transfer plants and well-located re-use centres enable more efficient transport of these materials. The establishment of quality criteria for recycled products can enable certification of the final product, thereby increasing its market acceptance. Digitalisation can support waste diversion at the building end-of-life by monitoring and controlling material use and by providing recycling companies with advance notice of the type and amount of construction, renovation and demolition materials that will be transported to them (see chapter 6).

3.8 Circular Strategies in New Buildings to Avoid Embodied Emissions

In cases where new construction is required, design strategies can be used that reduce the amount of material used and that prioritise the use of locally sourced, circular and bio-based materials with low embodied carbon. These materials can be used to build larger-scale, adaptable structures that align with the principles of the circular economy.

Adopting Circular Strategies in the Material Manufacturing and Design Phases

Construction practices based on "design for disassembly" can promote adaptable structures that make materials easily recoverable.

When new construction is necessary, it can incorporate circular design strategies that reduce the amount of material used. Decisions about material selection – such as choosing low-carbon materials (whether bio-based or reclaimed) – will greatly avoid the need for extracting and using non-renewable virgin raw materials. Additionally, construction practices based on design for disassembly can promote adaptable structures that make materials easily recoverable for re-use at the end of a building life.

Promising technological developments are emerging for cements and binders derived from the direct capture of CO_2 emissions that are generated at power plants and other industrial smokestacks (Cao et al. 2021) (see chapter 5). The decarbonisation potential is huge: if future building materials were derived from carbon capture, then even new buildings could potentially be carbon negative. If carbon-intensive materials (concrete or metals) need to be used, many strategies in the material processing and design phases can greatly reduce embodied carbon:

- Designing more efficient structural systems (e.g., standardisation of components, using mechanical joints instead of chemical joints) for ease of disassembly.
- Pre-fabricating components off-site to avoid waste and construction emissions. This can involve using factory-controlled methods that optimise material use and enable a component to be disassembled and reassembled into a future life cycle instead of being discarded. In some cases, off-site construction has reportedly reduced waste by up to 100 per cent (Chen, Feng et al. 2022).
- Making improvements during the production phase, such as electrifying (with renewable sources) as many processes as possible, and improving the mixtures for concrete and cement.

Selecting Locally Sourced, Circular and Bio-based Materials with Low Embodied Carbon

Innovators are working to increase the market share of low carbon and bio-based materials.

For the selection of new building materials, innovators are working on two major fronts to: 1) reduce the emissions of conventional building materials (see chapter 5), and 2) increase the market share of alternative building materials, such as reused and recycled materials as well as local, low-carbon solutions and bio-based materials (see chapter 4). Shifting from non-renewable to circular materials may help alleviate environmental stress from depleting raw mineral-based materials and promote circular flows of agricultural and other wastes (Churkina et al. 2020). (See chapter 4).

Advancements in bio-based material systems present opportunities to expand to multi-story construction, including adaptable structures that could support design for disassembly. These kinds of structures may offer the potential to sequester carbon during the material production, construction and use phases (John et al. 2009; Robertson, Lam and Cole 2012; Laguarda-Mallo et al. 2014; Keena et al. 2022). These benefits of a shift to bio-based materials are discussed in the next chapter.

SUMMARY

KEY DESIGN STRATEGIES TO IMPROVE CIRCULARITY IN BUILDINGS

Build less, and build with less

> Promote adaptive re-use and conservation of existing buildings to extend their lifetime. For new buildings, promote lightweight construction, using fewer materials, and mandate longer lifespan estimations.

Use performance-based building codes

> for embodied carbon, which facilitate upstream design strategies to design out waste and tackle carbon early. Performance rather than prescriptive-based building codes would be supported by whole life-cycle thinking and analysis.

Promote evidence-based material selection

> and awareness among building professionals of alternative low-carbon construction materials and components (both new and secondary materials) early on, to reduce long-term waste.

Promote selective deconstruction

> at the end-of-use phase, prioritising careful dismantling over demolition to support material recovery of building components and materials.

Design for disassembly and modular construction

> New buildings should be designed for disassembly and should use modular construction to enhance longevity and enable dismantling, thereby reducing expended embodied carbon.

Accelerate digitalisation of buildings

> to support waste diversion. Building information modelling and/or building passports can be used to monitor and control material use and to alert recycling companies of incoming end-of-use materials. Digitalisation can also facilitate assessing the quality of secondary materials before they re-enter the marketplace. Encouraging digitalisation in the construction process, especially for institutional and public buildings, will lead to a market transformation and facilitate the inclusion of these technologies in smaller buildings such as houses

4

SHIFT to Bio-based Building Materials

Moving towards more renewable materials requires sustainable resource management and incentivizing biodiversity.

4.1 Scaling Renewable Building Materials: Opportunities and Challenges

Renewable bio-based building materials can drive reductions in atmospheric carbon.

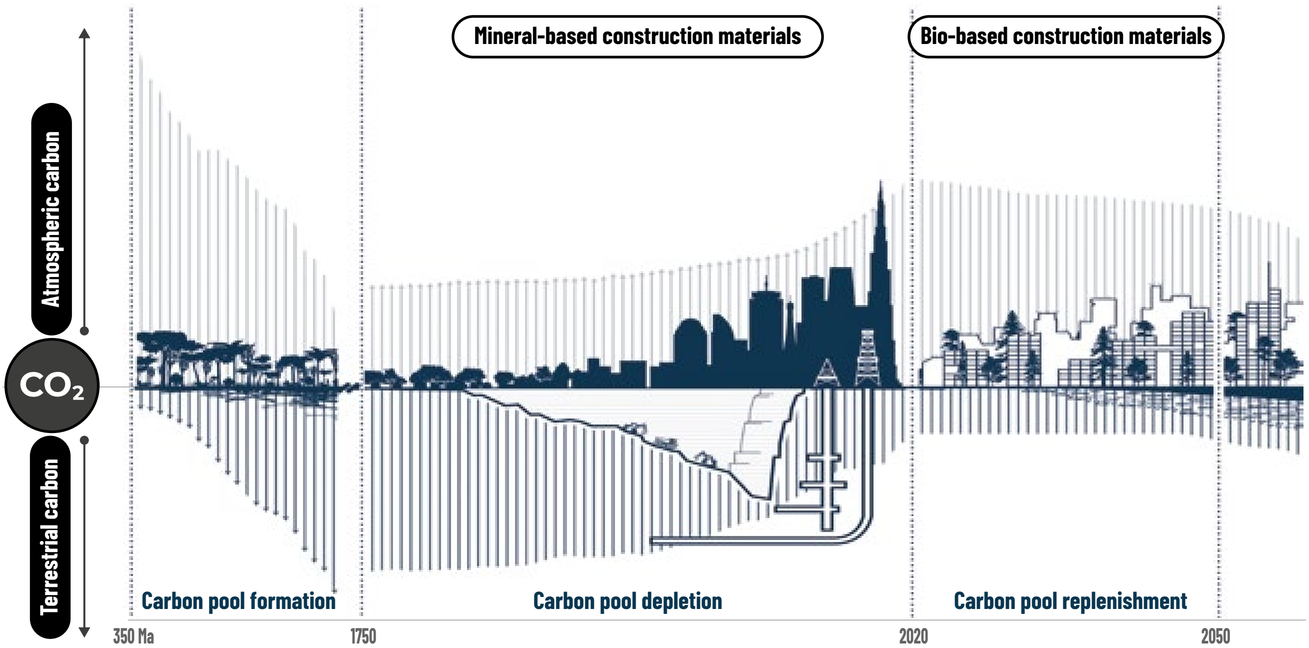
If managed responsibly, renewable bio-based building materials have a unique capacity to drive reductions in atmospheric carbon by: 1) matching renewable resources to building material applications, at lower carbon footprints, and 2) serving as a global carbon sink (see **Figure 4.1**). Timber is the leading bio-based building material being used at scale. Although promising technological product innovations are available to address rising demand for timber in developed countries, demand outpaces forest regrowth and relies on a limited range of tree species (Pomponi et al. 2020). Global timber demand has a large impact on tropical forests, especially since many tropical countries do not have sufficient financial and infrastructural resources to improve material efficiency and sustainable forest management.

More policy support is needed to encourage the use of waste biomass in building materials.

Increased investment is needed to develop regenerative methods of managing global forests and agricultural lands. The potential to redirect biomass residues into cost competitive construction products such as cementitious binders, bricks, panels and structural components, could incentivize more careful and productive management. Compounding benefits include the capacity to store carbon within building materials and products, thereby reducing climate change emissions from decaying matter, forest fires and the burning of crop waste. Further, major carbon sequestration benefits could come from new cooperative approaches between builders and forest managers to increase the biodiversity of forests through the selection of functional attributes for building materials according to species (Osborne et al., 2023).

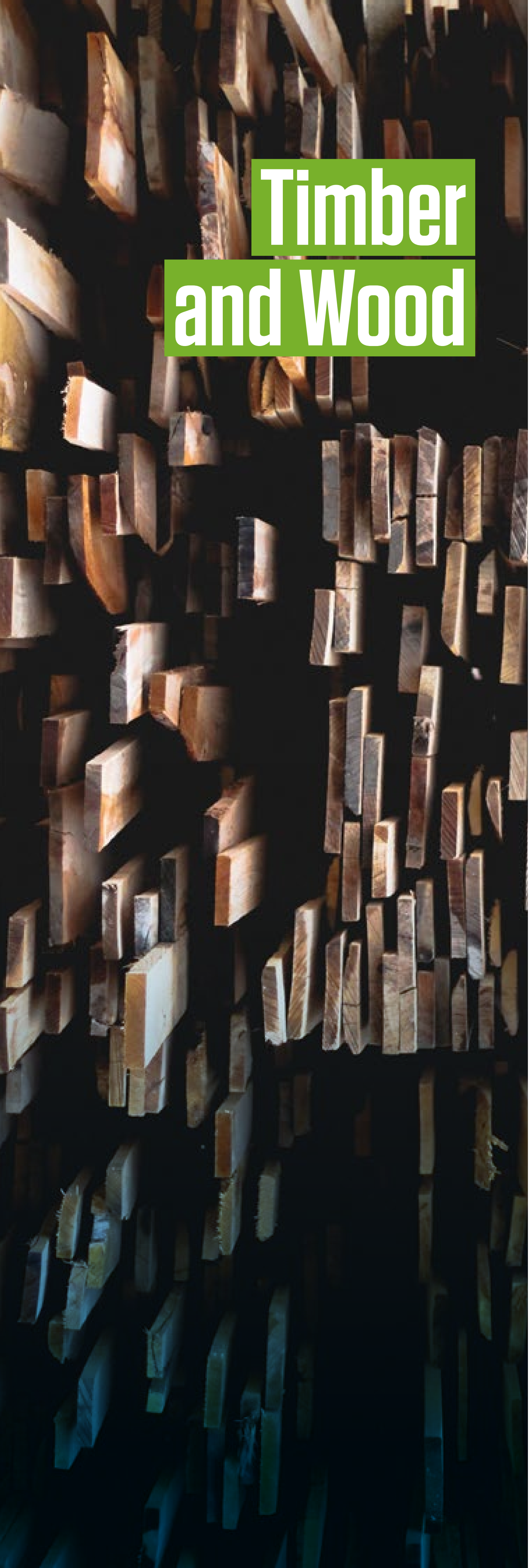
A promising avenue to alleviate pressure on timber resources is the development and use of reconstituted wood products from non-timber lignocellulosic residues from forestry, agricultural and food "waste." Today, most of the biomass from agricultural by-products is either abandoned on land (generating greenhouse gas emissions through natural decomposition) or burned (releasing carbon directly to the atmosphere). Within forests, excess biomass residues can feed and exacerbate wildfires (Sahoo et al. 2021). Meanwhile, in urban areas, waste biomass is typically either landfilled or combusted for energy recovery, both of which are more carbon-intensive pathways than converting this waste into valuable building materials (Tripathi et al. 2019; Lan, Zhang and Yao 2022). Scaling biomass residues from agriculture requires a biodiverse and material-efficient approach to avoid worsening the negative environmental and labour impacts of monoculture agriculture.

4.1 Historical development of atmospheric carbon patterns



A shift to bio-based building materials by 2060 can replenish the carbon pool and reduce atmospheric carbon

Note: The figure shows the historical transition in the terrestrial carbon pool from formation (left) to depletion (middle) to gradual replenishment (right, with simultaneous reduction in atmospheric carbon). Adapted from Churkina *et al.* 2020.



4.2 Timber and Wood

KEY MESSAGE

Recent advances in timber building material technologies offer the potential to replace carbon-intensive steel and concrete structures in some urban areas with mass timber. This provides the double benefit of reduced production emissions and long-term carbon storage in the building compared to mineral-based materials. However, it will be critical to prioritise appropriate afforestation practices, particularly in the natural forest regions of tropical countries, where logging rates far outpace effective replanting.

Mass Timber Has Great Potential to Replace Steel and Concrete and Reduce Emissions

Substituting conventional materials with mass timber could reduce global emissions 14-31 per cent.

In the last two decades, cross-laminated timber – a wood product made from the crosswise layering and lamination of structural grade timber – has become an attractive alternative to concrete and steel, due to its potential for scalability, sustainability, strength, and flexibility, as well as its suitability for incorporation into fast, modular off-site construction techniques (Mallo and Espinoza 2014; Brandner et al. 2016). Because cross-laminated timber has a comparatively high strength-to-mass ratio, it can be used for walls, floors and ceilings in hybrid reinforced concrete or steel systems in low- to mid-rise buildings, one of the fastest growing markets in emerging economies (Schmidt and Griffin 2013). In many cases, governments are modifying laws and national codes that previously restricted the use of timber construction systems in tall buildings, to now promote the use of wood (Umeda 2010; Sinclair 2019).

Local and regional studies have found that substitution practices using mass timber could reduce global CO_2 emissions 14-31 per cent and global fossil fuel use 12-19 per cent (Oliver et al. 2014; Pilli, Fiorese and Grassi 2015). More conservative estimates, however, show lower carbon storage potential and highlight the vulnerability of such models to market shocks (Johnston and Radeloff 2019). Mass timber buildings have demonstrated over 10 per cent lower operational energy compared to similar concrete buildings (Chen 2012). When accounting for 55 per cent recycling and 45 per cent energy recovery rates for end-of-life cross-laminated timber (John et al. 2009), mass timber buildings have shown 40 per cent emission savings and lower environmental impacts (John et al. 2009; Robertson, Lam and Cole 2012; Laguarda-Mallo et al. 2014).

As more country-specific studies (particularly in the developing world) examine the potential of timber building materials to store carbon and mitigate climate change, this can inform regional differences in the climate mitigation potential of wood products and develop incentives for sustainable forest management.

.

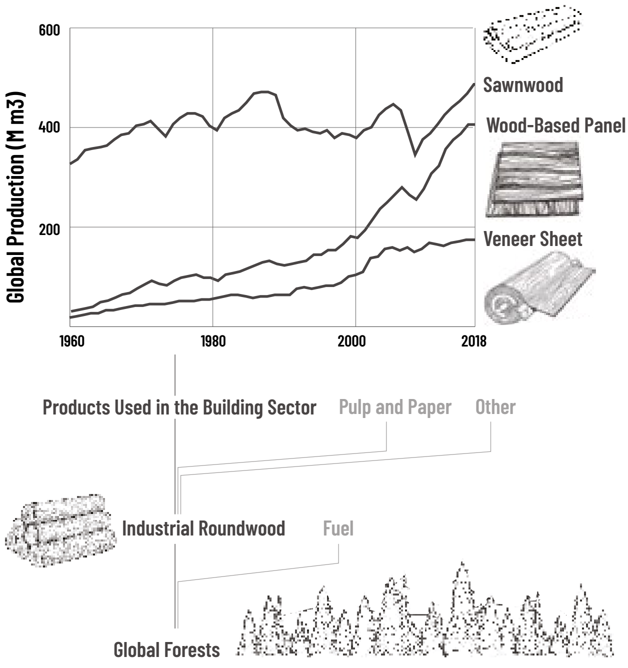
Safeguards Are Needed to Ensure Sustainable Timber Sourcing and Avoid Pitfalls

Forest certification and timber tracking practices could reduce wood waste by 14-184 per cent.

Timber has been used as a construction material and for diverse building products, such as structural beams, panelised boards, and walls and window framing. However, increased demand for such applications requires the establishment and implementation of safeguards that ensure responsible timber sourcing. In 2020, the global wood harvest came from two main sources: forest plantations (which accounted for 8 per cent of global cropland) and natural forest area (4 per cent of the global total) (Evans 2009; Mishra et al. 2022).

Currently, the overall rate of timber harvesting and deforestation in natural forests worldwide is faster than the overall regrowth of forests (Pendrill et al. 2019; Zhang et al. 2020). Timber demand is rising both in emerging economies, which use wood resources largely for fuel, and in developed countries, which use it mainly for building materials and paper products. Globally, the use of harvested industrial roundwood for products such as wood-based panels and veneer sheets increased significantly between 1960 and 2018 (see **Figure 4.2**).

4.2 Global trends in harvested wood products, 1960-2018



Use of industrial roundwood for wood-based panels and veneer sheets has increased significantly.

Adapted from FAOSTAT data from 1960-2018, in Steel *et al.* 2021.

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BOX 4.1

GROUNDING GENDER EQUITY AS A DRIVER WITHIN CIRCULAR ECONOMIES

Across the timber and biomass industries, gender norms and relations play a critical role in complex resource management and biodiversity conservation practices (Shiva 1992; Agarwal 2010; Kiptot and Franzel 2011). Global patterns of gender norms largely show that men participate in and manage seasonal forestry practices linked to cash income, whereas women have been responsible for the daily provision of forestry resources for food and broad household needs that lie outside of formally remunerated work (Shiva 1992; Agarwal 2010). In this sense, not only is the daily multi-tasking nature of women's labour largely invisible, but the likelihood of expanding women's participation in commercially productive roles is restricted due to the heavy workload.

Such norms are woven deeply into the social organisation of agricultural and industrial communities and have historically normalised the role of women and children as an informal community "support workforce" to service a primary male-dominated labour and management workforce (Arora-Jonsson 2014). This paradigm has led to policy gaps in valuing and supporting forestry extension services (Yokying and Lambrecht 2020; Nara, Lengoiboni and Zevenbergen 2021). Critically, when government policy focuses protection and job security solely on primary male forestry workers, this increases the dependence of the women-dominated workforce, particularly in terms of economic and land-use transition (Reed 2003).

Global studies have documented the role of women in the selection, propagation and marking of "wild" plant resources, effectively serving as biodiversity custodians (Shiva 1992; Howard 2003a; Howard 2003b; Kiptot and Franzel 2011). In China, women farmers have been the driving experts behind maize breeding (Shiva 1992; Song 1998; Song and Jiggins 2003). Studies in South Asia show the "snowball" impact of vertical mobility in female executive leadership positions, leading to increased female participation in timber resource co-management and decision-making (Agarwal 2010). In Sweden, while women represent 2 per cent of the construction sector workforce, a national study found that women accorded higher interest and importance to environmental issues but had lower influence on environmental outcomes (Wallhagen, Eriksson and Sörqvist 2018). Such patterns offer important foundations for destigmatizing and increasing women's environmental participation and leadership across all levels in the buildings and construction labour sector.

Given that women face barriers to accessing credit and loans, financial institutions need to service and design loan collateral systems that are suitable to individuals and women collectives (Demirgüç-Kunt, Klapper and Singer 2013). While financial inclusion serves as a basis for bringing women to the table, governmental programmes and policies need to expand women's access to new technologies, marketing information and training to sustain their participation on the ground (Kiptot and Franzel 2011; Coleman and Mwangi 2013; Agarwal 2015).

Currently, the overall rate of timber harvesting and deforestation in natural forests is faster than the overall regrowth of forests.

Relative to major end-uses such as fuel and paper, the conversion of timber into wood building materials offers huge carbon reductions because these materials can serve as long-term carbon storage over a building's lifetime (Churkina et al. 2020; Mishra et al. 2022). However, this model of building materials as a "carbon sink" assumes that sustainable replanting of trees occurs. Currently, this is the case only partially in Europe and North America, where the rising demand for wood products is coupled with a capacity for afforestation practices. In tropical and subtropical forests, increased logging drives dangerous levels of deforestation, ultimately reducing the long-term capacity of natural forests to sequester carbon (Vogtländer, van der Velden and van der Lugt 2014; van der Lugt et al. 2015).

In total, an estimated 38 per cent of the world's wood products are used in the built environment, roughly 1,800 million tons in 2020 (FAO 2020). Around 10-30 per cent of the timber traded worldwide is harvested illegally, a share that may reach 90 per cent for tropical hard and soft woods (Grace Farms Foundation 2022). Illegal logging operations are valued at up to $100 billion, or an estimated 10-30 per cent of the global timber trade (Grace Farms Foundation 2022). Globally, as much as half of illegal logging is dependent on forced labour. In addition to the hazardous nature of logging activities, exploitative conditions may include threats, poor living and working conditions, excessive work hours, non-payment of wages and debt-based coercion (Vidican 2020). Gender inequalities are also rife, with women often engaged in uncompensated informal work (see **Box 4.1**).

BOX 4.2

TAKING PRESSURE OFF WEST AFRICA'S TROPICAL FORESTS THROUGH THE USE OF NON-TIMBER BIOMASS RESOURCES

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In Senegal, local timber production supplies 5 per cent of the country's demand (Berthome, Silvertre and Kouame 2013) and relies primarily on wood harvested from the regions of Tambacounda and Kolda. However, key tree species in these areas are threatened, including linké (afzelia africana), caïlcédrat (khaya senegalensis) and dimb (cordyla pinnata) (Berthome, Silvertre and Kouame 2013). In 2020, Senegal also imported more than 100,000 tons of wood from elsewhere in West Africa, primarily from Côte d'Ivoire, the region's leading timber producer. Timber harvesting is also increasing in Ghana, where logging rates are estimated to be double to triple the legal annual allowable cuts, with adverse effects on both forest area and regional biodiversity (Oduro 2016).

Because of old milling equipment and the lack of operator training, timber production companies in West Africa lose an estimated 20-40 per cent of timber materials. This, in turn drives higher harvesting rates to make up for the loss (Asamoah et al. 2020). To accelerate circular practices on-site in such contexts, critical near-term actions include training and upskilling timber manufacturing workers and investing in upgrading of milling equipment.

Given the historical challenges and rising demand in West Africa's timber industries, there is an opportunity to reduce emissions and accelerate the development of market opportunities by substituting timber and structural materials with non-timber (plant-based) biomass resources, such as bamboo, coconut and typha composites. Local timber industry products can be used for flooring and window and door framing, and less-used timber species can be used for main construction activities (such as engineered bamboo due to its rapid growth rate).

Agricultural biomass feedstocks can generate fewer emissions in their production and store carbon during their lifetime in a building. However, investment is needed in the research and development and commercialisation of a wider range of agricultural feedstocks in West Africa. Current efforts evaluate the use of coconut husk by-products from the region's coconut food industry to manufacture medium to high-density fibreboards as an alternative to local reconstituted wood products (Lokko et al. 2016). Such studies show the impact of coconut fibreboard hygrothermal behaviour in reducing operational carbon (Lokko and Rempel 2018).

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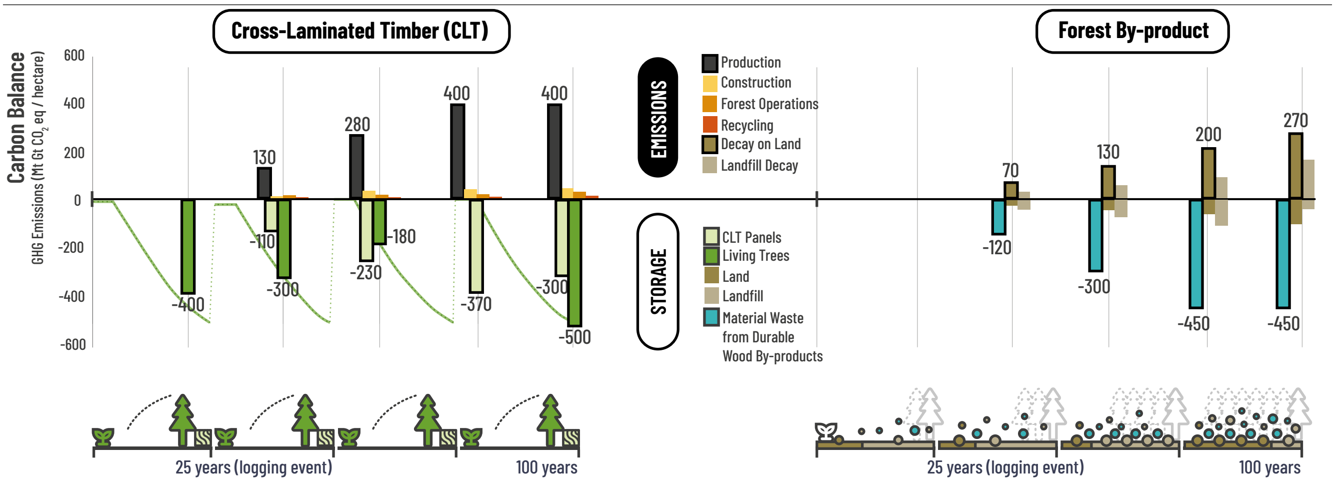
Most Carbon Emissions from Timber Production Are from Harvesting, Transport and Manufacturing

Timber-based building materials rely heavily on toxic, chemical glues and fossil energy.

Carbon emissions in the timber industry are concentrated in the phases of harvesting, transport and wood manufacturing (Steel, Officer and Ashley 2021). Previous estimates of CO_2 emissions from timber harvesting underestimated emissions associated with pesticides, fertiliser and herbicide use as well as "clear-cuts" (the decaying logs and residues from logging). Together, these account for an estimated 15 per cent of logging emissions (Lippke et al. 2011; Hytönen and Moilanen 2014). In the United States of America, even when long-term carbon storage in wood products is taken into account, the CO_2 emissions from timber logging and wood manufacturing exceed those from the residential and commercial sectors combined (Talberth 2019).

The manufacturing of structural beams, panels and engineered wood products relies heavily on the use of toxic, chemical glues and fossil fuel energy (Bergman et al. 2014). However, emerging timber-based materials such as cross-laminated timber and forestry by-products offer the potential to balance out these emissions over the building life cycle through carbon storage (Lan et al. 2020) (see Figure 4.3). As efforts to model the global storage of carbon in wood products advance, a key area for long-term CO_2 emission reduction is through improving harvesting practices and wood manufacturing processes (Buchanan and Levine 1999; Talberth 2019). Important efforts to advance improved harvesting practices and to reduce pressures on tropical forests are occurring in West Africa (see **Box 4.2**).

4.3 Embodied carbon balance of cross-laminated timber and forest byproducts



Producing cross-laminated timber both stores and emits carbon, and the use of by-products from the process also offers opportunities for carbon storage.

Note: Note: Transitioning to bio-based materials and timber involves both afforestation practices and circularity, as materials made from forest by-products can store carbon and offset emissions from decay. Source: Lan *et al*. 2020.

KEY STEPS TO

EXPAND THE SUSTAINABLE USE OF TIMBER AND WOOD IN BUILDINGS

Support and enforce sustainable natural forest management and afforestation practices

> Policies targeting the owners of industrial forestlands are key to improving sustainable management of natural forests and transitioning to productive plantations (Pirard, Dal Secco and Warman 2016).

> Policies and plans should encourage afforestation of a diversity of softwood and hardwood tree species and reduction in the use of chemical herbicides and fertilisers.

> Using biomass from clear-cuts as an on-site fuel source is a key near-term solution to avoid CO_2 emissions and fossil-based electricity use (Gustavsson and Sathre 2011; Bergman et al. 2014).

> For tropical forest production countries, adopting forest certification and timber tracking management practices could reduce emissions from deforestation and forest degradation by 29-50 per cent and improve carbon storage in sawn wood products and reduce wood waste by 14-184 per cent (Sasaki et al. 2016).

Enhance material recovery from forest by-products and wood manufacturing

> Clear-cuts and off-cuts from wood manufacturing have potential to serve as feedstocks for use in panelling, boards, furniture and flooring applications.

> Recuperation of forest detritus and upgrading infrastructures could minimise tree felling for primary timber and save vast amounts of carbon by helping to reduce forest fires (Yale Carbon Containment Lab 2022).

Transition wood manufacturing to renewable energy sources

> Encourage the upgrading of existing infrastructure to use of renewable energy sources in wood manufacturing.

Replace petrochemical-based glues, chemicals and coatings in wood products

> Replacing petrochemical glues with bio-based adhesives would reduce embodied emissions while improving the mechanical and hygrothermal performance of wood and reconstituted wood products.

Advance social acceptance of wood-based products in buildings

> Improve social acceptance and address regulatory barriers governing fire safety in buildings.

> Key policy incentives aimed at stimulating market demand are needed to broadly promote the use of

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4.3 Bamboo

KEY MESSAGE

Bamboo is a fast-growing renewable resource that has witnessed significant advances as a building material in the last two decades. However, to reduce the CO_2 footprint of bamboo products, investment is needed in the development of low-carbon, bio-based treatment chemicals as well as non-toxic glues for laminated products.

Bamboo Offers Excellent Properties and Can Be Used in Many Building Applications

Bamboo's high tensile and compressive strength offers a wide range of structural applications.

As a fast-growing grass, bamboo can serve as a renewable feedstock for a range of building material uses worldwide. With a tensile strength close to steel and a compressive strength twice that of concrete, bamboo is used for structural columns and beams, foundation, flooring, roofing and walls (Chung and Yu 2002; Hegde and Sitharam 2015; Lv, Ding and Liu 2019; Yadav and Mathur 2021). Progress in engineered bamboo shows mechanical performance comparable to that of heavy timber (Sun, He and Li 2020). Bamboo poles can be adopted for a range of scaffolding, shear wall and complex structures. Bamboo structures are key candidates for use in seismic (earthquake) and flood zones, towards expanding the use of bamboo in climate change resilience planning.

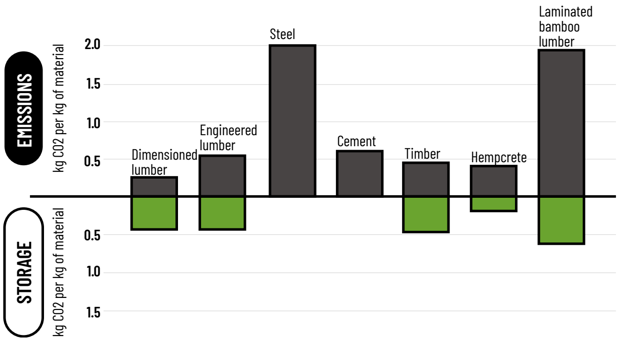
Bamboo Grows Quickly and Sequesters More Carbon Than Forests

Per hectare, bamboo sequesters 1.46 times the carbon of fir forests and 1.33 times tropical rainforests.

The bamboo plant has a rapid growth rate and can reach maturity in under five years; as such, bamboo forests can play a key role in carbon sequestration (Liese and Köhl 2015). Currently, bamboo forests occupy an estimated area of 36 million hectares globally, or around 3.2 per cent of the global forest area (Lobovikov et al. 2007; Phimmachanh, Ying and Beckline 2015). Globally, an estimated 30 per cent of bamboo is grown in forest plantations (Beena and Seethalakshmi 2011).

Bamboo is considered to be a frontrunner for driving afforestation practices to mitigate climate change. Global studies of the annual carbon sequestration capacities of bamboo range from 5 to 24 tons of carbon per hectare; on the lower end, this is 1.46 times the sequestration capacity of forests and 1.33 times that of tropical rainforests (Yen and Lee 2011; Nath, Lal and Das 2015; Yuen, Fung and Ziegler 2017). Unlike the carbon sequestration losses associated with timber logging, selective bamboo harvesting may be less ecologically damaging to forests, and productive species can yield between 150-296 tons per hectare of forest plantation land (Seethalakshmi,

4.4 Carbon emissions and storage for laminated bamboo versus other building materials



Laminated bamboo products generate similar emissions as steel but offer carbon storage potential.

Source: Xu et al. 2022.

Jijeesh and Balagopalan 2009).

The global availability of land for scaling up bamboo plantations is decreasing.

However, the global availability of land for scaling up bamboo plantations is decreasing, in direct competition with other land uses, particularly for housing and agriculture (Seethalakshmi, Jijeesh and Balagopalan 2009).

Current Treatments Used in High-Quality Bamboo Products Are Carbon Intensive and Need Further Development

Current practices for chemically treating bamboo rival the emissions of producing steel.

Most of the carbon emissions from bamboo products are generated during the production stage, which relies on a range of toxic treatment chemicals to improve the material's resistance to mold and corrosion. The use of synthetic treatment chemicals, glues and high-temperature air for drying can lead to the tripling of CO_2 emissions relative to timber-based products (Xu, Xu et al. 2022). Per unit of volume, studies demonstrate that laminated bamboo products can generate carbon emissions comparable to those of steel (see Figure 4.4). However, unlike steel and cement, bamboo also offers carbon storage potential, at levels slightly higher than for some other harvested wood products. Overall, bamboo's carbon emissions potential is around 63 per cent, whereas its carbon sequestration potential is around 37 per cent (Xu, Xu et al. 2022).

Due to the high carbon emissions and ecological impacts of chemicals used in the treatment of bamboo, progress is needed towards the development of low-carbon, eco-friendly alternatives. Current approaches include water leaching as well as processes that rely on botanical preservatives and the use of effluents from paper milling production (Kaur et al. 2016); such processes occur largely in small-scale, experimental operations today. Key ways to reduce emissions from bamboo manufacturing include re-using bamboo products at their end-of-life and providing on-site renewable energy (Vogtländer, van der Velden and van der Lugt 2014).

KEY STEPS FOR

SCALING BAMBOO AS A SUSTAINABLE BUILDING MATERIAL

Expand policy support for low-carbon alternatives in bamboo manufacturing and treatment

> Incentivise commercial-scale bamboo industries to use bio-based alternative chemicals for treatment.

> Manufacturers must gradually phase out the use of toxic, fossil fuel-based chemicals and glues.

> Research and investment are needed in the development of non-toxic, bio-based treatment chemicals and glues for laminated bamboo products.

Develop and promote the use of bamboo material standards

> Key engineered bamboo standards provide guidance on the testing and standardisation of engineered bamboo performance for structural design (ISO 2004a; ISO 2004b; ISO 2022a).

Promote sustainable bamboo forest plantation management practices

> Highly productive and sustainable plantation management practices can be accelerated, with 63 per cent of resources privately owned, unlike timber where 80 per cent are government-owned (Lobovikov et al. 2007).

> Large and growing demand for bamboo in countries like China provides an opportunity for sustainable management outcomes, much as the rise in demand for timber products helped drive afforestation and carbon sequestration practices in Europe and North America (Lou et al. 2010).

Transition bamboo production to renewable energy sources

> Transitioning to renewable energy sources for manufacturing is critical given the energy requirements of bamboo manufacturing, particularly during the treatment and production stages.

Scale the bamboo planting stock

> Bamboo cultivation depends on seeds from flowering plants (Seethalakshmi, Jijeesh and Balagopalan 2009; Singh et al. 2013), but the shortage of planting stock is a key barrier to expanding bamboo's carbon storage potential.

> Novel cultivation methods include offset planting, culm and branch cutting, and rhizome planting.

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4.3 `Biomass

KEY MESSAGE

Non-timber lignocellulosic material streams generated from forestry, agriculture and biomass residue streams represent key local building material solutions. Globally, models of the annual biomass supply outweighs projected construction demand. If scaled up to substitute or reduce the use of petrochemical and timber-based building materials, fast-growing lignocellulosic materials can lower the projected peak in CO_2 emissions, shifting it by 50 years. However, such materials today represent a small market share of building materials and rely on expensive and complex processing techniques. Both "push" and "pull" market approaches are needed to scale up and ensure widespread adoption of bio-based building materials. Policies that financially incentivise the capture and value addition of biomass building materials need to be coupled with marketing and education programmes.

Supplies of Biomass Residues Outweigh Current and Projected Construction Demand

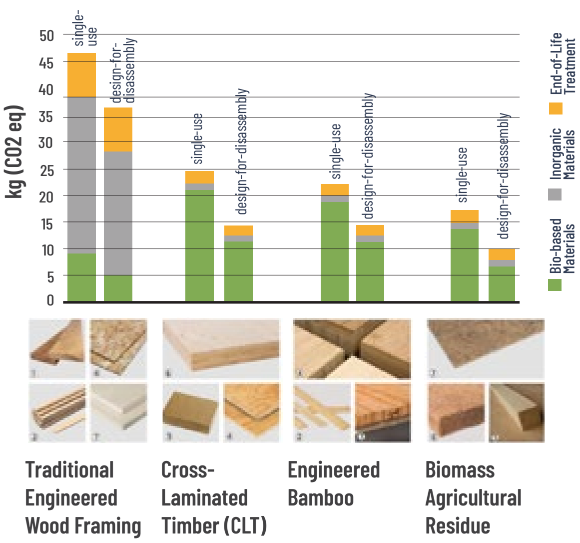
Building materials from forestry, agriculture and biomass residues are key local solutions.

Non-timber lignocellulosic materials generated from forestry, agriculture and biomass residue streams represent key local building material solutions. Current models of bamboo and straw, two fast-growing renewable biomass resources, show that annual supply outweighs demand (Göswein et al. 2022). Each year, an estimated 140 gigatons of by-product biomass is generated worldwide (Tripathi et al. 2019). Current end-of-life pathways for biomass, such as landfills and incineration for energy recovery, miss out on the true opportunity for value addition and carbon storage in long-life building materials (Langholtz, Stokes and Eaton 2016; Lan, Zhang and Yao 2022).

Biomass-Based Construction Can Result in Lower Carbon Emissions

While cross-laminated timber assemblies are advocated as the key load-bearing alternatives to concrete and steel, such approaches overlook the inability of the current timber supply to meet projected demand. In general, when compared with traditional wood frame construction, wall systems made from cross-laminated timber, bamboo and coconut-biomass agricultural residues demonstrate much lower CO_2 emissions and environmental impacts on a life-cycle basis (Keena et al. 2022) (see Figure 4.5). Across these bio-based material assemblies, design-for-disassembly strategies, which

4.5 Comparison of life-cycle carbon dioxide emissions per square metre for four wall assembly types



Wall systems made from cross-laminated timber, bamboo and coconut-biomass residues show emission savings.

Adapted from Keena et al. 2022.

enable component re-use, have been shown to result in 10-50 per cent CO_2 emission reductions (Keena et al. 2022).

If scaled up to substitute or reduce the use of petrochemical and timber-based building materials, fast-growing ligno-cellulosic biomass can lower the projected global peak in CO_2 emissions, shifting it by 50 years (ibid.). However, coordination must be improved along the supply chain to avoid increased emissions from biomass collection, treatment and mechanical processing. Biomass feedstocks can be of poor or non-standardised quality, and their availability can be highly distributed or erratic.

Living biomass systems can reduce operational carbon emissions in buildings.

In addition to biomass-based materials, the integration of living biomass systems—such as green roofs, façades and indoor wall assemblies—in buildings can bring decarbonisation benefits by reducing heating and cooling loads, while also having the potential to improve air quality (see **Box 4.3**).

Strawbale Insulation Has Proven Carbon Benefits

Straw biomass offers a low-carbon opportunity to replace petrochemical-based insulation.

Straw biomass offers a critical opportunity to replace high-carbon petrochemical-based insulation. Straw is the widely available leftover stalk harvested from a diverse range of fast-growing cereal plants, such as wheat, maize, rice and other grains. Compared with conventional insulation materials – including polystyrene, mineral wood, cellulose fibres and rock wool – straw bale insulation demonstrates much lower CO_2 emissions (Koh and Kraniotis 2020), with the market opportunity for bio-based insulation growing.

When integrated into walls, straw has demonstrated the ability to reduce operational carbon. Load-bearing strawbale houses have been found to have a carbon footprint of between 20 and 1,000 kilograms of CO_2 per square metre, compared to more than 600 kilograms of CO_2 per square metre for conventional construction (Bocco 2014; Bocco Guarneri 2020; Koh and Kraniotis 2020). This wide carbon footprint range highlights the importance of design for effective integration.

Carbon Benefits of Myco-Based Biomass Still Need to Be Demonstrated at Scale

Myco-based materials harness fungi's capacity to transform biomass into building products.

Another promising bio-based option that has emerged over the last two decades is the use of mycelium, the vegetative state of fungi. Myco-based building materials are gaining attention due to fungi's capacity to bind a wide range of cellulosic components of agricultural, forestry and food biomass waste streams into chitin-bound building insulation, fibreboard, particle board and bio-brick products. However, more research is needed on the scalability of methods and the carbon footprint of these materials.

Due to the requirements for high-quality biomass, myco-production entails high levels of refrigeration and drying, requiring the use of plastic moulds and sterilisation. Mycelium enterprises are often unable to obtain sufficient supplies of high-quality, consistent, single-stream biomass and may turn to importing high quality feedstocks, further driving up emissions.

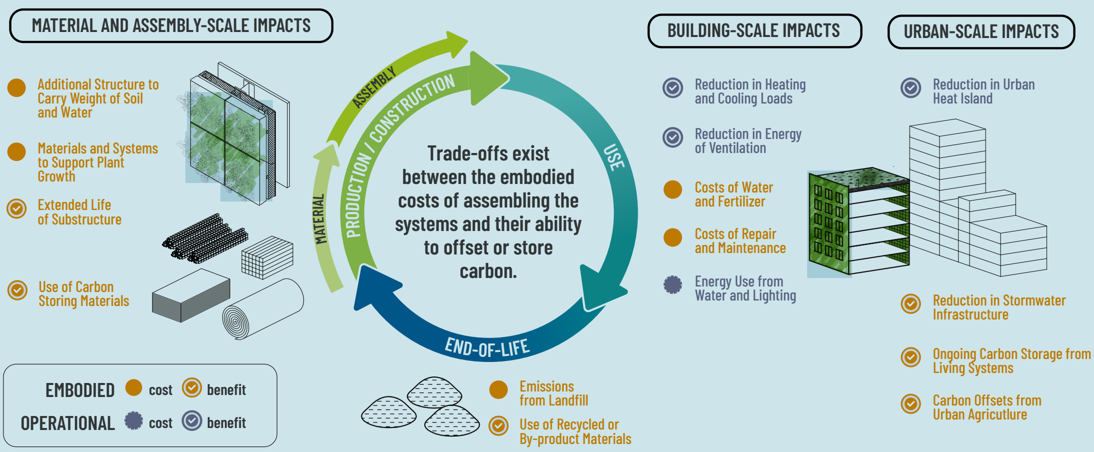
Overall, advancements have been made in developing material requirements as well as production and construction standards for biomass-based building materials. However, to accelerate their uptake in both retrofits and new construction, financial incentives are needed to promote development of methods alongside circular, biodiverse design approaches.

4.6 Examples of green building envelopes using living biomass and other climate-friendly features

Living systems have shown promise in reducing heating and cooling loads and the urban heat island effect.

Source: ARUP 2016.

4.7 Relationship between embodied and operational carbon within living biomass material systems



Trade-offs exist between the embodied costs of assembling the systems and their ability to offset or store.

Source: Ciardullo and Dyson 2022.

BOX 4.3

THE BENEFITS OF INTEGRATING LIVING BIOMASS SYSTEMS IN BUILDINGS

Many municipalities globally have recognised the benefits of integrating vegetated surfaces or living materials (plantings, soils, and structures that support them) as a solution to reduce urban carbon emissions (Liberalesso et al. 2020). Such living biomass material systems – including green roofs, façades and indoor wall assemblies (see **Figure 4.6**) – can offer ecosystem services that have been displaced by urban hardscaping (Manso et al. 2021; Shafique et al. 2018)

Compared with conventional materials, living biomass material systems provide comparable or improved energy savings from insulating and cooling effects (Shafique et al. 2020; Bevilacqua 2021; Theodosiou 2009)). Some living wall systems contribute up to 58.9 per cent energy savings compared with exposed concrete wall systems, particularly in high-sun areas (Coma et al. 2017). In addition, such systems have consistently been shown to reduce the urban heat island effect (Santamouris 2014; Shishegar 2014) and to offset the carbon costs of urban stormwater infrastructure (Berndtsson 2010; Wang, Eckelman and Zimmerman 2013).

In indoor applications, living systems can improve air quality and reduce the energy costs of mechanical ventilation (Feng and Hewage 2014; Torpy, Zavattaro and Irga 2017; Mankiewicz et al. 2022). The ability for exterior systems to actively participate in ongoing carbon sequestration is still under investigation (Whittinghill et al. 2014). One study concluded that converting all exposed concrete building roof areas in the U.S. city of Detroit to low-profile green roofs would have the same carbon savings as removing 10,000 sport utility vehicles from the road (Getter et al. 2009).

Each living biomass system is highly dependent on design-specific elements, including the type of structure used, the choice of plant species and growing media (see Figure 4.7). Design choices reveal an integrated relationship between embodied and operational carbon (Ciardullo et al. 2022; Mankiewicz et al. 2022, Kosareo and Ries 2007, Koroxenidis and Theodosiou 2021; Rowe et al. 2022; Susca 2019). For example, systems that require additional materials for irrigation systems or for sub-structures that carry the weight of soil and water can have higher embodied carbon (Ottele et al. 2011). However, this relatively small increase in material might be offset by operational carbon savings, as additional soil thickness and water-holding capacity has more impact on reducing heating and cooling loads (Raji, Tenpierik and van den Dobbelsteen 2015, Rowe 2011).

The embodied costs of biomass systems might be offset in the future through the use of recycled, renewable and lightweight material substrates (Rincon et al. 2014; Chenani, Lehvävirta and Häkkinen 2015; Tams, Nehls and Calheiros 2022), organic fertilisers (Chafer et al. 2021) and system designs that reduce water use (Natarajan et al. 2015). Because many benefits of living biomass material systems manifest at the urban scale, municipalities should expand incentives for these systems to help offset initial and ongoing maintenance costs.

KEY STEPS FOR

SCALING BIOMASS AS A SUSTAINABLE BUILDING MATERIAL

Improve management of the biomass supply chain

> Provide opportunities for small and medium bio-based enterprises and start-ups in order to compete with well-established reconstituted wood and petrochemical insulation industries (Langholtz, Stokes and Eaton 2016).

> Integrate approaches to land use, residue management, and the creation of eco-manufacturing firms in order to lower the costs of biomass collection, increase availability, and improve quality control and product standardisation

Encourage biomass use in buildings, rather than for short-lived energy and industrial applications

> Incentivise industry to use biomass for longer-life applications, as short-lived applications, such as fuel or paper products, drives up emissions.

Create incentives to encourage the conversion of biomass into building materials

> Policy support is needed to encourage the conversion of biomass feedstock to materials such as bio-based insulation, bio-aggregate products, and alternatives to timber and wood products.

> Both "push" and "pull" market approaches are required to scale up adoption.

> Policies that financially incentivise intersectoral collaboration need to be coupled with consumer campaigns and technical training for architecture, engineering and construction stakeholders.

Reduce the potentially high embodied carbon associated with biomass-based materials

> Coordination and research must be improved along the supply chain to avoid increased carbon emissions from biomass collection, treatment and mechanical processing.

Promote just labour practices in biomass industries

> A critical lever for biomass industries in the near term is to ensure qualitative gains across the whole life cycle, including ensuring healthy and just labour conditions and environments (Heerwagen 2000; Loftness et al. 2007).

5

IMPROVE

Conventional Building Materials and Processes

Due to the ongoing global construction boom in developing economies, it is imperative to prioritise the decarbonisation of conventional material production and mandate the design of circular components for concrete, steel, aluminium, glass and plastics.

5.1 Decarbonizing Conventional Building Materials

In the near term, non-renewable materials will continue to comprise the majority of building materials.

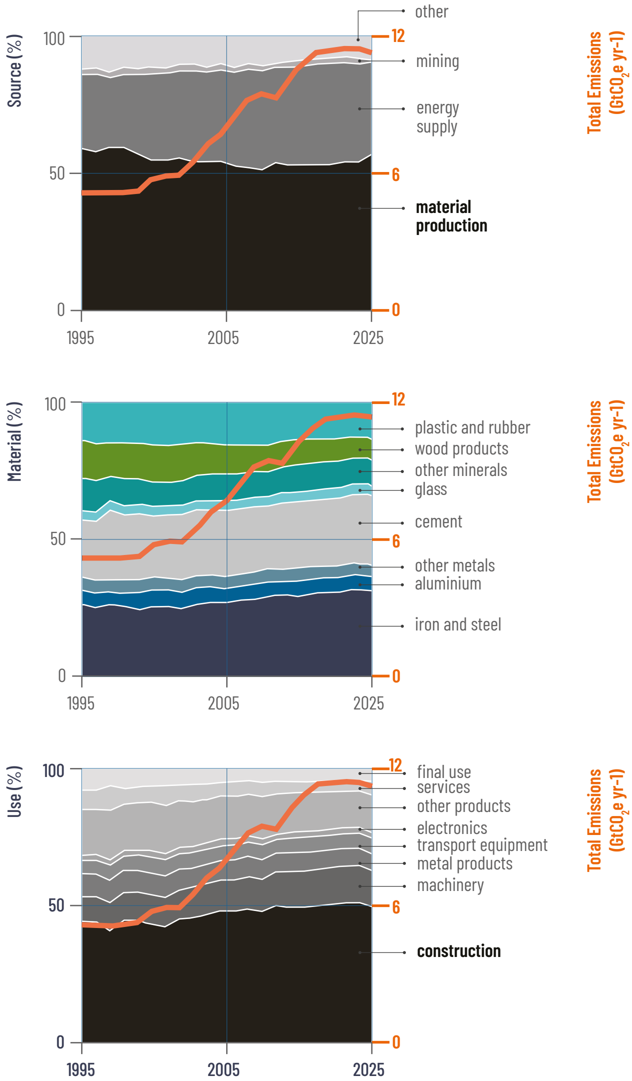
Within the construction sector, cement and concrete, as well as iron and steel, play a dominant role (see **Figure 5.1**). In addition to their emission impacts, many of the most common building materials are not-renewable, meaning that raw material supplies are finite and cannot be replenished. Conventional non-renewable materials – cement/concrete, steel, aluminium, petroleum-based plastics and glass – will continue to comprise the majority of building materials for decades to come, and cannot always be replaced with renewable alternatives.

Given their ubiquity and rising demand, it is critical to decarbonise the major conventional building materials and process, pursuing parallel but very different pathways. Additionally, promising avenues exist to scale up the use of "transitional" building materials, specifically earth-based masonry products, which are non-renewable but typically have lower emissions. These include adobe blocks, compressed earth blocks, fired bricks, and Typha clay composites, which can serve as potential substitutes for high-carbon cement-based blocks if certifications and standards are developed and enforced.

In addition to their emission impacts, many of the supply chains for conventional building materials are at high risk for unethical working conditions. The materials with the highest risk of being made with forced labour are rubber, glass, fibre and textiles, steel, electronics, bricks, timber, stone, copper, iron and minerals. As conventional materials are increasingly decarbonised, it is essential that fair labour considerations are coupled with environmental policy targets. (To support decision-making on these combined socio-economic impacts, see the *Design for Freedom Toolkit*, Grace Farms Foundation 2022.)

Key to all efforts will be electrifying and decarbonizing the energy that is used to produce and maintain buildings and materials across their life cycle. In addition, regions can avoid the extraction of resources by shifting from unsustainable mining of materials towards integration of renewable components and methods. Reducing raw material extraction and harvesting can also mitigate many social ills such as forced labour issues upstream in the supply chain. To advance the circularity of conventional building materials, the supply of recycled content will need to catch up with the growing demand for materials.

5.1 Shares of total greenhouse gas emissions by source, material class and industrial sector



Cement dominates the emissions impact of construction, followed by steel.

Source: Hertwich 2021.

Concrete and Cement

5.2 Concrete and Cement

KEY MESSAGE

The concrete and cement sector has a disproportionate impact on greenhouse gas emissions and will continue to do so for many decades. Even if all of the existing methods to reduce the climate impacts of the sector were successfully implemented and scaled, additional funding would still be urgently required for public-private partnerships to accelerate the development, demonstration and commercialisation of decarbonisation strategies. Key strategies include: 1) chemical carbon reduction of concrete and cement production techniques; 2) carbon capture and storage at manufacturing plants; 3) design for disassembly and re-use of components; 4) novel (bio-based) concrete mixtures to reduce binder requirements; and 5) computer-assisted and additive manufacturing to reduce carbon emissions from transport and on-site construction waste.

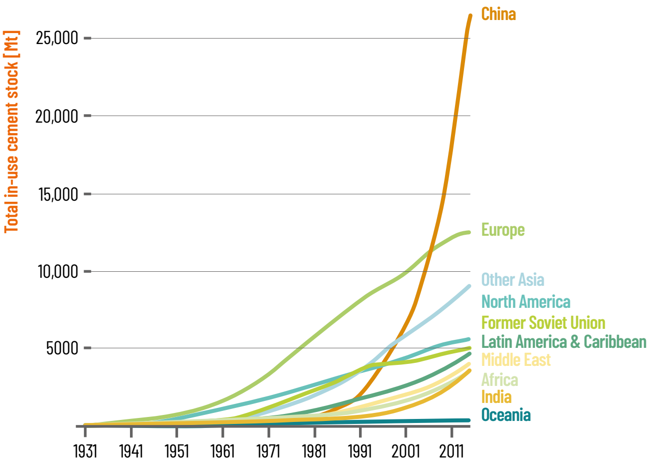
Concrete Is Widely Used in Buildings and Construction But Is Not Always Needed

Many concrete buildings of less than 12 storeys could shift to bio-based structural assemblies.

Concrete is by far the most widely used construction material in the world, due in part to its strength and durability. It is produced by mixing cement and water with an aggregate, typically sand or gravel. In 2020, 4,300 million tons of cement were produced globally (IEA 2022a). Concrete mixtures are used for both residential and non-residential buildings and for infrastructure (e.g., railways, bridges).

Concrete has experienced 10-fold growth over the past 65 years, compared with a 3-fold increase in steel production and near-stagnant growth in timber production (Monteiro, Miller and Horvath 2017). Globally, in-use cement stocks – the amount of cement embedded in existing buildings and infrastructure – have surged in Asia, while they are flattening in Europe and North America (see **Figure 5.2**). Since the mid-2000s, China has built the world's largest in-use cement stocks, mostly in its buildings (80 per cent) and to a lesser extent in its infrastructure (20 per cent) (Cao et al. 2017).

5.2 Total in-use cement stocks, by region, 1931-2014



In-use cement stocks have surged in Asia but are flattening in Europe and North America.

Source: Cao *et al.* 2017.

In many applications, including housing, concrete is used where lower-carbon materials could suffice, largely because concrete has a developed supply chain and infrastructure, with ease of use and calculation. Many concrete buildings of less than 12 storeys could shift to bio-based structural assemblies for everything but the foundation and elevator shafts, if sustainable materials were available.

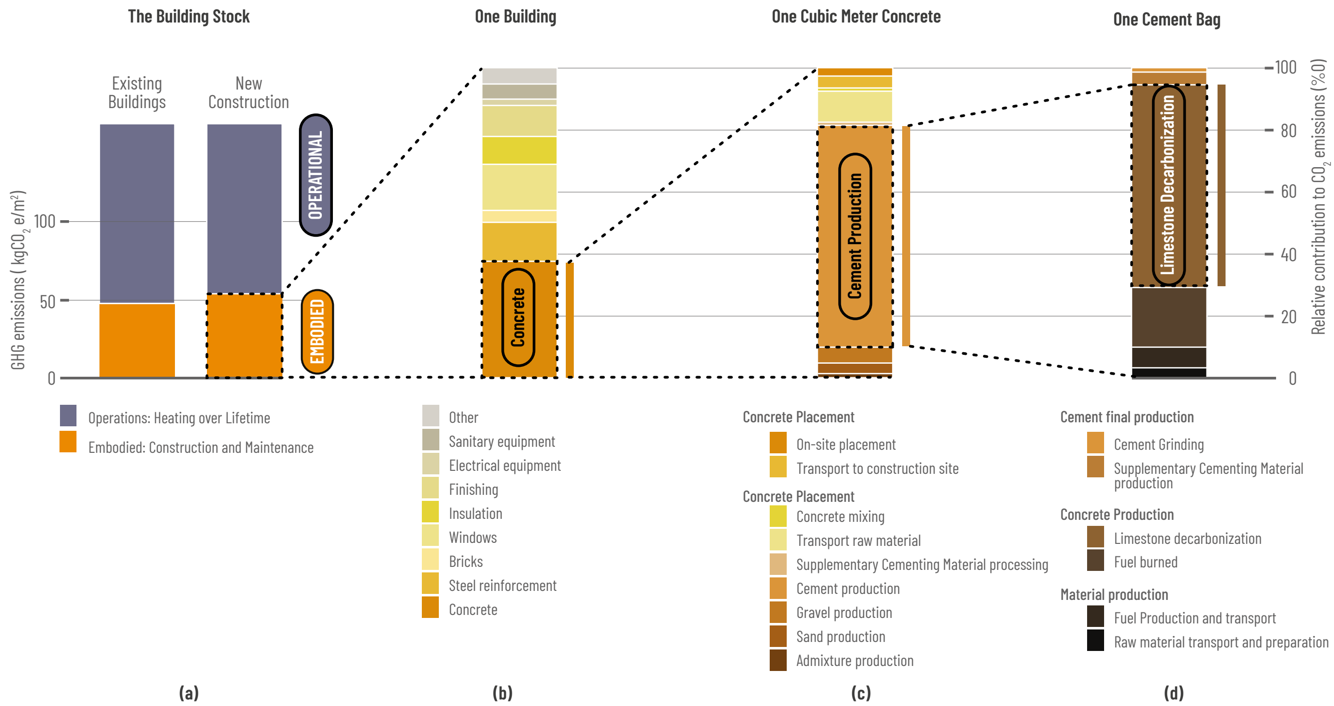
Concrete Contributes to Rising Global Greenhouse Gas Emissions, Among Other Impacts

Cement production accounts for 7% of global CO_2 emissions.

In cement manufacture, raw materials are milled to a homogeneous powder before being heated at high temperatures into clinker. The clinker is blended with gypsum to produce cement (IEA 2018a). Cement is the binding material in concrete, typically comprising around 10-15 per cent of the total (Habert et al. 2020). However, cementitious materials are by far the most carbon-intensive to produce, with cement production accounting for around 7 per cent of global CO_2 emissions (Hasanbeigi 2021).

Cement production is considered to be one of the most diffi-

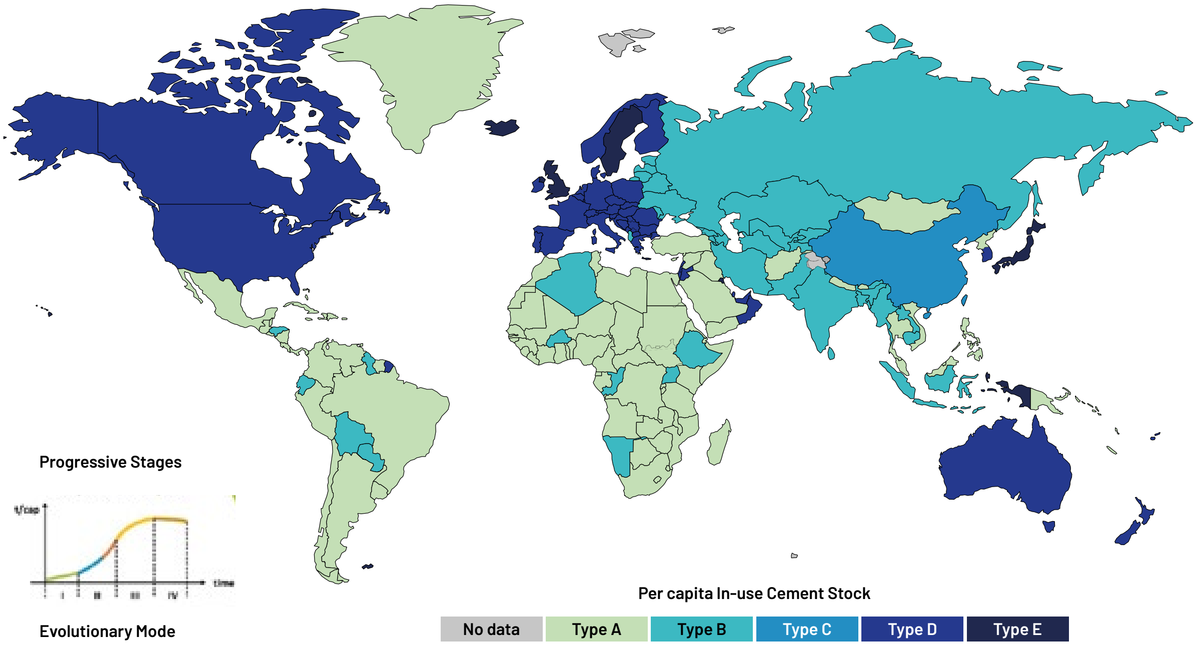
5.3 Dominance of concrete and cement in the embodied emissions of newly constructed buildings



Within concrete production, the main emissions are from cement production, in particular limestone processing.

Note: Figure (a) compares the operational (heating/ventilation/cooling over lifetime) and embodied (construction and maintenance) greenhouse gas emissions from the existing global building stock versus new construction. Figure (b) shows that for new construction, the largest emissions from a typical multi-family concrete building come from concrete production. Figure (c) shows that within concrete production, the main emissions are from cement production, in particular limestone processing (d). Source: Habert *et al.* 2020.

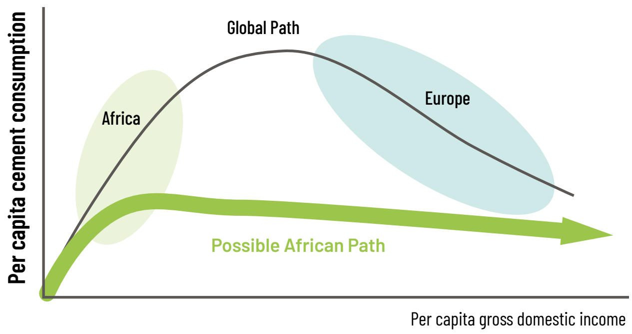
5.4 Evolutionary stages of per capita in-use cement stocks, by country



Future growth in cement use will likely be highest in Africa and South America, followed by Asia.

Note: The colouring of countries follows the progressive stages of per capita cement use shown in the chart at bottom left. Source: Cao *et al.* 2017.

5.5 Potential for regions to leapfrog towards more wealth and less carbon-intensive cement



Through material efficiency strategies and low-carbon production, countries can decouple cement use from income.

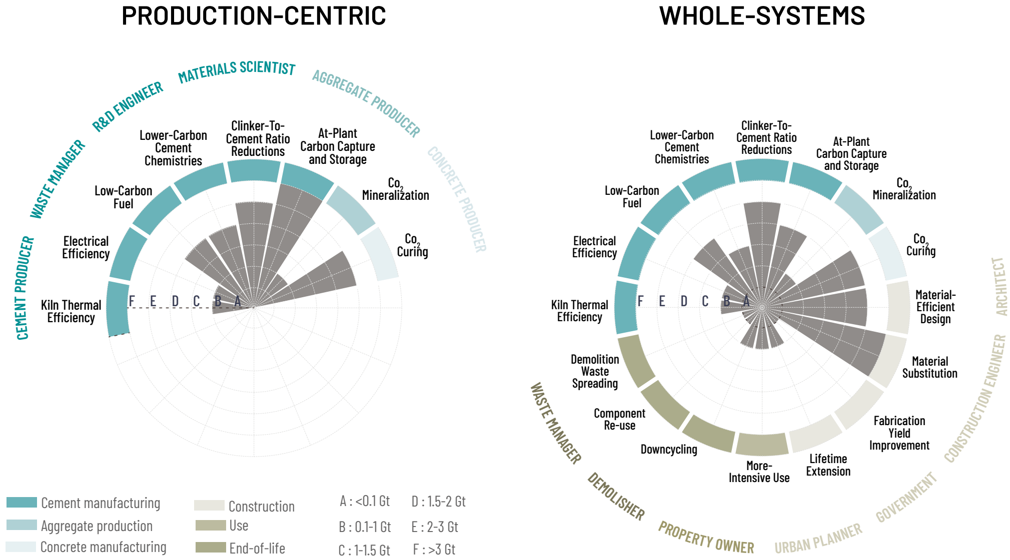
Source: Adapted from Schmidt 2017.

cult industrial processes to decarbonise (Davis et al. 2018). This is because the majority of the carbon emissions (55-70 per cent) are released in the chemical process of converting limestone to calcium oxide; another 30-45 per cent of emissions stem from fuel combustion during the production process (IEA 2018a; Cao et al. 2020). Overall, producing one ton of clinker in a modern cement plant can generate around 600 kilograms of CO_2 (Fennell, Davis and Mohammed 2021). Electrification of cement production with renewable sources can substantially lower emissions.

For new construction, the largest embodied emissions from a typical multi-family concrete building are from cement production, in particular the processing of limestone into clinker (see Figure 5.3). This points to the urgent need to reinvent the cementitious binders used in concrete mixtures. Traditionally, ordinary Portland cement has been used as the binder to produce concrete and mortar; however, it is the material responsible for the highest CO_2 emissions in cement production.

To address rising emissions from the sector, the substitution of conventional cement components with low-carbon alternatives is key, such as by-products from industrial, agricultural, forestry and end-of-use sources. In the near term, cement demand can be reduced using available means by efficiently optimising the ratio of cement in concrete mixes and reducing rampant waste in construction due to lack of oversight and certification.

5.6 The whole-systems pathway results in emission reduction through more efficient use of cement and concrete



Note: The figure illustrates the possibility to expand the levers for decarbonisation in the United States of America, China, and India through whole life-cycle stakeholder accountability. Each grey bar in the circular bar charts corresponds to the sum of cumulative net CO_2 savings across the cement and concrete cycle by 2060 in the buildings and road sectors for the three countries. Source: Cao et al. 2021.

Concrete has other negative environmental impacts across its life cycle. In urban areas, concrete, along with asphalt surfaces, absorb more heat than natural vegetation, disproportionately contributing to urban heat island effects (Mohajerani, Bakaric and Jeffrey-Bailey 2017) and to the rising global demand for carbon-intensive cooling and air-conditioning systems. The impervious surfaces created by concrete and asphalt contribute to surface run-off, polluting waterways and causing soil erosion and flooding.

Developing Countries Have an Opportunity to Leapfrog Global Trends in Concrete Use

Since the early 2000s, China and other Asian countries have dominated global cement demand, accounting for 80 per cent of cement production in 2014 (Rissman et al. 2020). The region's high use of cement has surged to meet the infrastructure needs of an expanding middle class. This rapid growth is in line with a study across 184 countries that links per capita in-use cement stocks to levels of affluence (Cao et al. 2017). The study found that as countries develop economically, they go through five progressive stages: from little cement use per capita (A), to a take-off stage with high growth rates (B and C), followed by a slow-down stage (D) and eventually a shrinking stage (E) (see **Figure 5.4**).

The figure shows that Africa and South America have the lowest per capita in-use cement stocks (green) followed by most of Asia (blue). China is in a phase of rapid growth (red), whereas Europe, North America and Oceania no longer have strong growth in cement stocks (yellow). Japan and Sweden, meanwhile, are seeing a decline (brown), which is attributed in part to successful material efficiency strategies that allow for the same building and infrastructure services but with less cement use. These historical patterns suggest that China's rapid growth in cement use could reach saturation in the near future, and that future growth will be highest in Africa and South America, followed by the rest of Asia.

However, it will be crucial to break the global pattern of rising cement use while simultaneously increasing the living standards and urbanisation rates of low-income countries. Ideally, these countries will implement a mix of material efficiency strategies, coupled with low-carbon cement production, that enables them to leap-frog towards higher affluence with relatively low per capita cement consumption (see **Figure 5.5**) (Schmidt 2017). A key enabling tool will be reduction of the clinker-to-cement ratio by using novel supplementary cementitious materials from forestry and agricultural by-products.

Even with a shift towards bio-based materials, the rapid growth in urban density and infrastructure in developing countries means that the high-carbon cement and concrete sector will continue to soar for the foreseeable future.

Alternative, Low-Carbon Cement Binders Can Replace Portland Cement and Reduce Emissions

With many regionally available options, most major cement-producing countries could substitute alternative low-carbon options.

Significant potential to decarbonise cementitious materials exists along their life cycle, with the largest opportunities occurring in the production stage (57 per cent), followed by manufacturing (23 per cent) and end-of-use (14 per cent) (Pamenter and Myers 2021). During production, the use of alternative, low-carbon materials for concrete binders presents the largest decarbonisation potential (see **Annex 2**). Unlike for fly ash and granulated blast furnace slag, there is no supply shortage for many alternative secondary cementitious materials, especially bio-based ones derived from agricultural by-products.

The road to net zero concrete by 2060 will require replacing Portland cement with the many regionally available options being explored around the globe from agricultural, forestry and industrial by-products, as well as from end-of-life materials (see Annex 2). Most major cement-producing countries could generate enough of these alternative materials to substitute most of their demand for Portland cement, with the primary outlier being China, the world's largest producer of Portland cement (Shah et al. 2022). The study estimates that the theoretically achievable lowest clinker-to-cement ratio is around 0.14 globally, reflecting a 61 per cent reduction in the use of Portland cement compared to the current average (0.75).

Whole Life-Cycle Thinking Will Enable More Efficient Methods and Use of Cement and Concrete

Engaging stakeholders across the value chain offers flexibility on the path to net zero.

With a focus on the three largest cement producers and consumers globally – the United States of America, China and India – **Figure 5.6** describes two distinct pathways to achieve net zero emissions in the cement and concrete sector by 2060. These are: a production-centric pathway that relies entirely on the efforts of cement and concrete producers to mitigate emissions from the sector, and a whole-systems pathway that engages a broad range of actors – from producers to designers and recyclers – to implement more efficient methods and use of cement and concrete (Cao et al. 2021).

The whole-systems pathway results in an overall reduction of demand (and therefore emissions) through a more efficient use of cement and concrete in the built environment. As a result, it is less dependent on the need for maximum measures at the production level. In other words, engaging with all stakeholders across the value chain offers much-needed flexibility on the pathway towards net zero emissions by 2060. This includes a growing importance of the end-of-use stage, as the massive quantities of structures dating from the mid-20th century are due for replacement.
Engagement of stakeholders across the life cycle is key to integrate both production-centric and whole-systems decarbonisation scenarios (Cao et al. 2021). For whole-systems approaches to be adopted, mechanisms for knowledge sharing and transfer need to be established among producers, architects, developers and building maintenance operators. However, even if all the existing levers are incentivised, immediate actions are needed to galvanise research and development of innovative methods. Merely capitalising on current opportunities will not be enough to achieve net zero emissions by 2060.

More radical but still speculative methods for carbon capture during production show promise but require further analysis and development. Carbon capture and utilisation for concrete production (CCU concrete) has been projected to save between 0.1 to 1.4 gigatons of CO_2 by mid-century, and there are claims to extremely significant enhanced structural performance (ICEF 2016). However, there are conflicting opinions as to whether the benefits in increased strength and optimisation of materials will outweigh the carbon costs of capturing, transporting and incorporating the captured CO_2 into concrete products. To scale these technologies, it will be critical to verify the enhanced compressive strength from CO_2 curing and mixing, while ensuring that all electricity used in CO_2 curing is supplied through renewables to produce a net CO_2 benefit from CCU concrete (Ravikumar et al. 2021).

BOX 5.2

EMERGING RESEARCH ON STORING CARBON DIOXIDE IN CONCRETE

Capturing carbon in concrete production is an active area of research around the world. However, the exact amounts of CO_2 that could be absorbed by concrete are uncertain. This approach should be considered emerging and is not yet included in emission inventories overseen by the United Nations Framework Convention on Climate Change. At the University of California at Los Angeles, a research project is under way to upcycle carbon by taking CO_2 directly from the exhaust stream of a coal plant and transforming it into concrete building blocks. In Canada, the company CarbonCure claims to have delivered 2 million truckloads of concrete injected with CO_2, saving 132,000 tons of CO_2 (Fennell et al. 2022).

KEY STEPS TOWARDS

DECARBONIZING CEMENT AND CONCRETE

Shift to renewable electricity in cement production

> The highest priority for cement decarbonisation is to electrify the grid and the means of production, using renewable energy resources such as solar and wind power.

> Electric kilns should be the standard for any newly built cement plants (Global Cement and Concrete Association [GCCA] 2020; IEA 2022b).

Prioritise locally sourced alternative binders to reduce the clinker-to-cement ratio

> Portland cement contains more than 90 per cent clinker (a clinker-to-cement ratio above 0.9).

> Blending can reduce the clinker-to-cement ratio to around 0.75. In a net zero scenario, this could go down to 0.69 by 2025 and 0.56 by 2050 (Pamenter and Myers 2021; GCCA 2022; IEA 2022b).

> Reducing the clinker-to-cement ratio to 0.5 and below could be achieved using (bio-based) secondary cementitious materials. Local protocols would be needed for testing and certification.

> Use of calcined clay limestone (LC3) could reduce the clinker-to-cement ratio to 0.5 using existing technologies, and is close to commercialisation (Scrivener et al. 2018; Fennell et al. 2022).

> Including lime clasts in cement mixtures could provide durability and extend the life of concrete applications, resulting in energy savings (Seymour et al. 2023). However, building codes and design practices will need to adapt to the variable material properties (Scrivener, John and Gartner 2018).

Avoid unneeded concrete use through training, building standards and design

> Material scientists need to be educated on the plethora of new cement production technologies so they can optimise the material input and technology for the given context; this requires better communication among scientists, structural engineers and architects (Schmidt, Alexander and John 2018).

> Regularly updating building codes to account for these technological advances will be key, ideally coupled with incentives for manufacturers to produce the most low-carbon cement and concrete.

> Material efficiency should be a key consideration in building design, avoiding overspecification and using concrete only in those applications that require its outstanding structural properties.

> Changes to building codes, alongside education of architects and engineers to use best available technologies, could save over 25 per cent of cement by reducing overengineering (IEA 2019).

Use digital methods to improve material efficiency and allow for pre-fabrication

> "Design for circularity" and systems integration can revolutionise material flows through the use of digital methods and artificial intelligence. Industry must be supported to adapt and modernise.

> Digitalisation across the cement life cycle (via improved process controls, next-generation measurement devices) can improve efficiencies and reduce emissions (Fennell, Davis and Mohammed 2021).

> Moving inefficient and emission-intensive on-site construction to factory-controlled fabricated assemblies can reduce on-site pollution and increase the use of circular, recyclable components.

> An industry-wide effort is needed to reduce material consumption, optimise structures, and design customised parts through pre-fabrication and digitised construction, which produces an inventory of circular components for future disassembly and re-use (see **Box 5.1**).

> Standards need to rely on performance-based metrics rather than prescribing outmoded conventions, so that cement production can be adapted to local needs (Scrivener, John and Gartner 2018).

Improve concrete through carbon capture and storage, which has partial future potential

> Capturing and storing carbon (either underground or within materials to enhance material strength) is critical to reduce emissions from cement production.

> To achieve the International Energy Agency's scenario for net zero emissions, around 95 per cent of CO_2 emissions from cement would need to be stored by 2050, up from just 5 per cent by 2030 (IEA 2022a). Currently, less than 0.1 per cent of all global emissions are captured and stored.

> Because the CO_2 stream needs to be almost pure to store it cost effectively, research is urgently needed on more viable methods to scale up carbon capture and storage (see **Box 5.2**).

> Carbon capture and storage cannot be the only answer. Relying solely on improvements in these technologies within the cement and steel industries will require a 14,000 per cent increase in carbon storage capacity by 2050; meanwhile, in the last 10 years, the world has witnessed a 30 per cent reduction, rather than increase, in carbon storage capacity (Global CCS Institute 2020)

Urgently innovate cement and concrete recycling

> Currently, less than 1 per cent of concrete is made from recycled materials (Cao et al. 2020; Pamenter and Myers 2021).

> Design for circular recycling and reuse has lagged in the cement and concrete sector, even as these materials have disproportionate impacts on operational carbon across many climates.

BOX 5.1

ON-SITE PRE-FABRICATION OF MODULAR CONCRETE COMPONENTS IN BOTSWANA

D Design optimisation of modular components can greatly reduce the use of concrete for environmental control systems, leading to energy savings and future circularity. Architects and engineers for the Botswana Innovation Hub have developed methods for creating prefabricated modular concrete components using an on-site "mobile factory." These include hollow-core concrete slabs for buildings that greatly reduce the amount of steel and equipment needed for ducting and environmental control systems (see **Figure 5.7**). The slabs could lead to operational energy savings in buildings of 20-50 per cent and to reduced peak cooling loads of 70-90 per cent.

Computer aided design greatly aided the material optimization at every step of the lifecycle from design to delivery of fully automated, paperless, direct-to-fabrication techniques for the construction of the concrete building envelope modules. Concrete as a material choice is further justified in this example as it supports the planting of substantial green roofs with native flora and fauna that adapt and co-exist on the site and are able to retain substantial water and biodiversity.

The additional living biomass further dramatically lowers the building cooling requirements, and thus its operations energy expenditures. The prefabricated concrete modules also contain the moulding of interior channels for all of the systems to travel through the slab, which not only reduces materials required, but enables systems to be more space efficient, reducing the overall volumes required by the building. This could represent a very substantial savings on structural material requirements, especially for taller buildings such as towers, where the structural materials to resist wind loads increases with height.

5.7 Creation of hollow-core concrete slabs at Botswana Innovation Hub

Design optimisation of modular components can greatly reduce the use of concrete.

Source: From Top to Bottom: Botswana Innovation Hub (SHoP Architects; Buro Happold Consulting Engineers); Right Center: Vortex Extruder on-site "mobil factory"; Left Center: Pre-fabricated modular hollowcore concrete (Spiroll); Bottom: Scheme of a Termodeck slab (Spiroll)

5.3 Steel

KEY MESSAGE

Steel is an indispensable construction material today and a critical component of building and transport infrastructures. However, even with the emerging shift among some steel producers towards 100 per cent renewable energy in the production phase, and although steel is very well suited to recycling (potentially reducing up to 75 per cent of embodied carbon), the highest goal is to avoid the use of steel in buildings where possible and to shift to proven low-carbon alternatives, since steel is a non-renewable material and demand is increasingly outpacing the supply of recycled steel sources.

Global Steel Use in Buildings and Infrastructure Is Rising

More than half the world's steel is used in the construction of buildings and infrastructure.

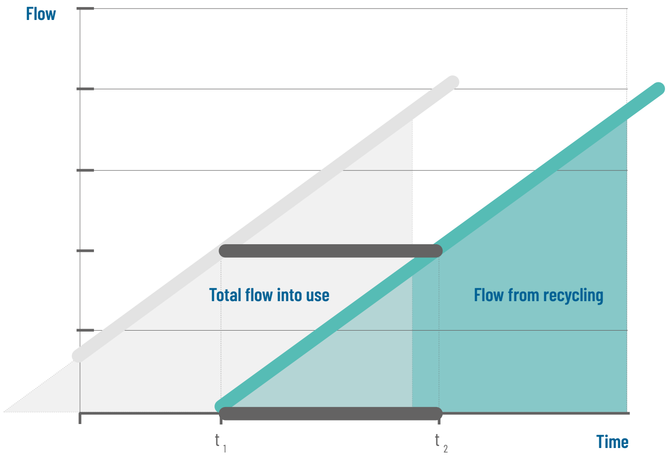
Steel is the second most abundant material used in buildings, at 360 million tons in 2008 (Cullen, Allwood and Bambach 2012). It is perhaps the building material that is most associated with modernisation and is a cultural indicator of economic progress, given its role in developing infrastructure. Annual steel production in 2021 was 1,950 million metric tons, with current growth rates of around 3 per cent (World Steel Association 2022). Production is anticipated to increase substantially by 2030 (IEA 2020).

Of the total iron and steel produced worldwide, 55 per cent goes into the built environment sector, split across buildings (33 per cent) and infrastructure (22 per cent) (Cullen, Allwood and Bambach 2012). In commercial and tall buildings, steel is used for the primary structure as well as to reinforce concrete. It is also used widely as the primary material for fitting out mechanical systems for heating, ventilation and cooling (HVAC).

As a primary and preferred structural building material, steel combines tensile strength with low cost, but it can also come with a high human cost. There are many points of potential forced labour along the steel supply chain due to the hazardous conditions and lack of transparency, ranging from extraction and smelting to production, rolling and erecting (Grace Farms Foundation 2022).

5.8 The time delay in the recycling of metals

The long lifetime of steel products has limited the amount of scrap available.



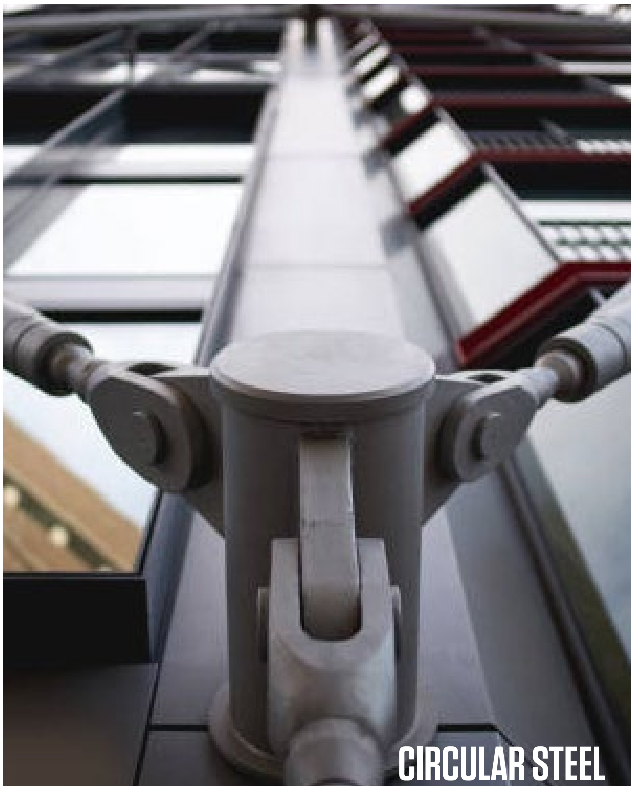
Note: Most metals have an average lifetime of around 20 years before they become available for recycling, and even longer when used in buildings. These long lifetimes combined with high growth rates in the past explain why metals will continue to be made primarily from virgin materials rather than from scrap. Source: UNEP 2011.

Steel Is Emission Intensive, Driven by Blast Furnace Technology

Unless policies incentivise greater material efficiency, cost structures will favour using more material.

The iron and steel sector is energy and emissions intensive, accounting for 8 per cent of global final energy use and 7 per cent of direct energy-related CO_2 emissions (IEA 2020). In steel production, most emissions are generated during three processes: when steel is produced from primary raw materials (using a blast furnace or basic oxygen furnace), when carbon is needed as a reducing agent (provided as coke derived from coal, releasing CO_2) and from the energy used to heat the melt.

A number of technical options exist for increasing the material efficiency of steel (thereby reducing use and overall emissions). These include: adopting lightweight design, reducing yield losses, diverting manufacturing scrap, re-using components, creating longer-life products and intensifying steel use (Allwood et al. 2013; Raabe, Tasan and Olivetti 2019). An example for extending the building lifetime is using galvanised steel for rebar in concrete, since galvanising protects the steel from corrosion and therefore avoiding the risk of failure. However, unless policies incentivise greater material efficiency, existing cost structures will tend to favour more material over less labour (Allwood 2013).



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There are two main approaches to reduce carbon emissions from steel production: 1) to continue using carbon-based methods but to couple this with carbon capture technologies, and 2) to replace the carbon (coke) used in reduction, the chemical conversion of iron ore into pig iron, with alternative reductants such as hydrogen or direct electrolysis (Rissman et al. 2020). Moving to renewable energy sources in production offers the greatest potential to reduce the embodied carbon of steel (Raabe, Tasan and Olivetti 2019).

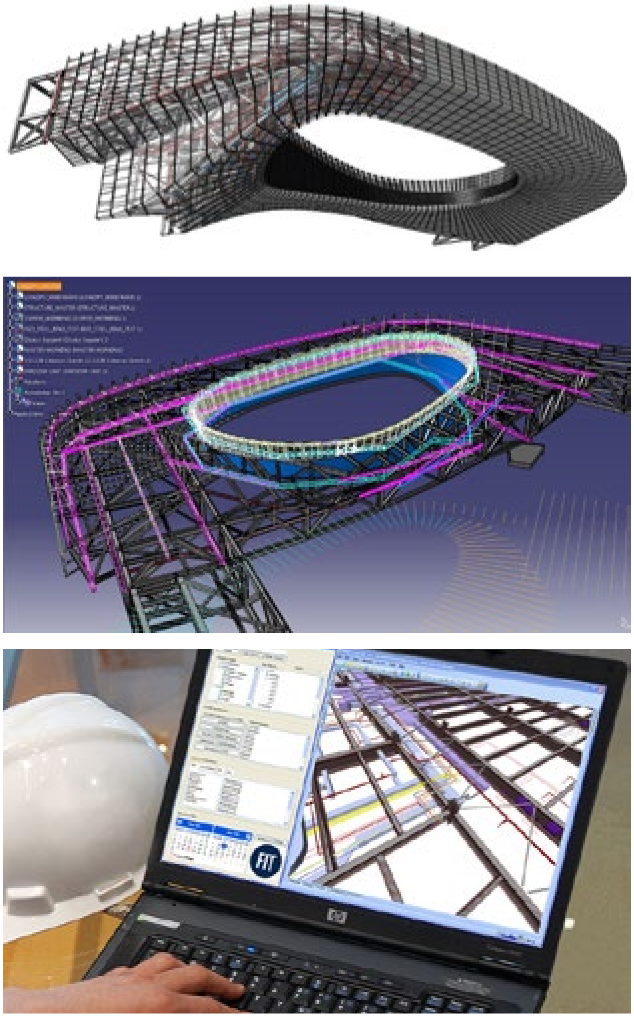
Making Steel From Scrap Will Reduce Emissions, But Recycling Rates Are Already High

Making steel from scrap saves 60-80% energy, but the scrap supply is limited.

An alternative way to produce steel is by using scrap as a raw material ("secondary production"), which occurs in an electricity-powered electric arc furnace. Producing steel from scrap requires 60-80 per cent less energy than primary steel production (UNEP 2013; IEA 2020) and does not entail chemical reduction (hence no input of coke, or heated coal). These massive energy savings also result in cost savings for producers; thus, the use of scrap as an input material is already very high, leaving only modest room for improvement. In certain markets, steel is already being recycled at over 90 per cent (IEA 2020).

The biggest challenge to wider use of secondary steel production is the limited amount of scrap. A large gap exists between the supply of recycled material and rising demand.

5.9 Circular Steel – Barclays Center, Brooklyn New York



The Figure above shows a contemporary digitised design and material component tracking process for the steel components of a sports arena in Brooklyn, New York City. The ability to track materials and their assemblies by digitising all phases of the life cycle, from design conception through construction management and reuse through a Building Information Model (BIM) is enabling decarbonisation strategies on many levels, from material optimisation, increased productivity at every stage, design for disassembly and reassembly, and reduction of on-site emissions through prefabrication of components.

Credit: Thornton Thomasetti Consulting Engineers, SHoP Architects

As a result, 35 per cent of all steel is made from scrap (World Steel Association 2023). The reasons for the limited amount of scrap are the long lifetime of steel products (20 years or more in buildings), combined with the rapid growth in demand in recent decades (see Figure 5.8). As long as demand continues to rise, the gap between scrap supply and demand will further widen, preventing the major carbon benefits from using scrap rather than virgin metal. This concept also applies to long-lived materials such as concrete, plastics and glass.

KEY STEPS TOWARDS

DECARBONIZING IRON AND STEEL

Improve the quality and collection methods of scrap steel

- In a circular steel economy using only scrap, measures would be needed to minimise contamination.
- As more scrap is used in metal production, concerns about the quality of recyclables increase, with copper contamination being of highest concern (Daehn, Serrenho and Allwood 2019; Cooper *et al.* 2020).
- Measures to minimise contamination include design for recycling, better sorting and the deployment of scrap refining technologies (Cooper *et al.* 2020).

Improve production with direct reduced iron ore technology and renewable energy

- Transitioning all steel production to best available technologies can save up to 26 per cent energy; better boilers can save up to 10 per cent, and using heat exchangers in refining can reduce power demand by 25 per cent (Napp *et al.* 2014; Gonzalez Hernandez, Paoli and Cullen 2018; Fennell *et al.* 2022).
- Primary steel production through the direct reduced iron process followed by an electric arc furnace avoids the need for coke as a reducing agent, leading to a reduction of 61 per cent in carbon emissions if methane-derived gas and renewable energy are used, respectively (Fennell *et al.* 2022).
- Using only hydrogen for the direct reduced iron process could reduce emissions by 97 per cent (Fennell et al. 2022), but this will depend on access to competitively priced green hydrogen, which is limited in supply and faces upscaling challenges (Castelvecchi 2022; Odenweller *et al.* 2022).

Avoid overuse of steel by selecting the appropriate product for the building's lifetime

- Materials need to be selected with the entire building lifetime in mind, not just the production stage.
- Carbon steels are the default metal of choice for reinforced concrete and as structural materials.
- Using corrosion-resistant stainless steels in marine environments makes it possible to design for longer building lifetimes, avoiding costly and carbon-intensive maintenance and repair. Correct material selection in marine environments is critical because most urban growth will occur along coastlines.
- In the International Energy Agency's most ambitious decarbonisation scenario, extending the lifetime of buildings would contribute to more than 90 per cent of the CO_2 emission reductions for both steel and cement by 2060 (IEA 2019).
- Avoiding overspecification is a key opportunity to minimise material use, both in material selection and in the amount of material used. For example, there is no need to use corrosion-resistant stainless steel rebar for inland applications.

5.4 Aluminium

KEY MESSAGE

Aluminium production is highly energy intensive when produced from ores, whereas producing aluminium from scrap can reduce the energy demand by 70-90 per cent. Bringing the aluminium sector on a path to near net-zero emissions is possible through a combination of actions, most importantly switching to low-carbon (renewable) electricity, deploying near-zero-emission refining and smelting technologies, improving the sorting of scrap, designing alloys for recyclability and reducing demand through material efficiency.

Aluminium Has Wide-Ranging Applications in Buildings and Construction

The buildings and infrastructure sector uses more than a quarter of all aluminium produced.

With a market share of 25 per cent, the buildings and construction sector was the largest end-use sector for aluminium in 2020, using 21 million tons of aluminium (CRU Consulting 2022). In construction, aluminium is used for roofing and cladding (37 per cent), windows and doors (27 per cent), curtain walls (18 per cent) and other components (18 per cent) (Allwood and Cullen 2012).

Aluminium is produced using both primary mined materials and (to a lesser extent) aluminium scrap, which consists of both end-of-use and new (industrial) scrap. The volumes of industrial aluminium scrap are currently much higher than for other engineering materials, indicating the potential for substantial improvements in the material efficiency of aluminium (Cullen and Allwood 2013).

Aluminium from Primary Mined Ores Is Extremely Carbon Intensive

Switching from fossil fuels to hydrogen and near zero-emission electricity is a key priority for a low-carbon aluminium future.

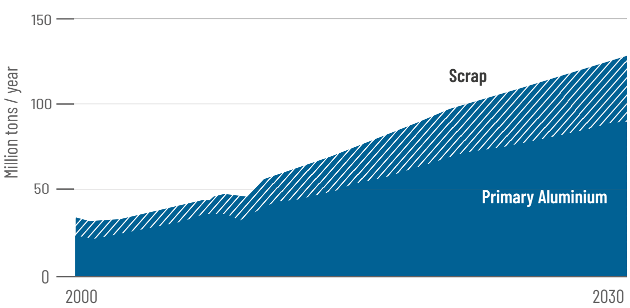
In 2021, aluminium production contributed over 3 per cent of the world's direct industrial CO_2 emissions (IEA 2022c). Producing aluminium requires refining the bauxite ore into alumina and smelting it into metallic aluminium, the latter being by far the most energy-intensive step, accounting for three-quarters of the energy used (Gutowski et al. 2013). In primary aluminium smelting, electricity accounts for 81 per cent of the greenhouse gas emissions (Mission Possible Partnership and IAI 2023). Decarbonizing aluminium will require near zero-emission technologies for refining and smelting, switching from fossil fuels to near zero-emission electricity, and higher recycling rates (currently 70 per cent) (IEA 2022c).

Supplies of Aluminium Scrap Are Limited But Increasing

Even if all aluminium were recycled, this scrap would only replace less than half of current demand.

Primary bauxite ore continues to be the main raw material in aluminium production, although the share of secondary scrap is increasing (see **Figure 5.9**). In 2019, 34 per cent of aluminium was produced from scrap (IAI 2021). As with steel, scrap supplies are limited due to rapid growth and long lifetimes (over 20 years). Even if all end-of-life aluminium were recycled, the scrap would only replace less than half of today's aluminium demand (demand in 2020 was twice that of 2000). By 2050, the share of scrap in aluminium production could equal that of primary ore (IAI 2021), even as production continues to rise (see **Figure 5.10**). If the demand for aluminium were reduced through material efficiency measures, it could represent an even higher share.

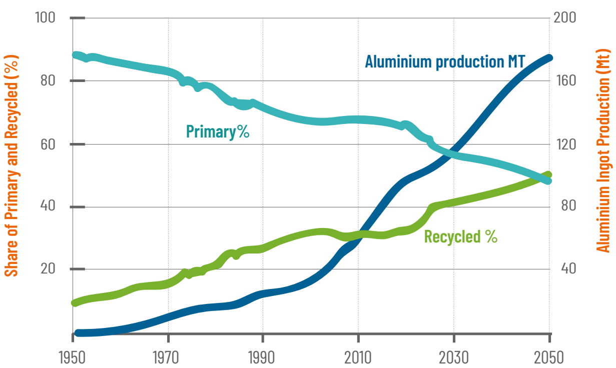
5.9 Historic and projected global aluminium production by source (2000-2030)



Globally, the share of aluminium from scrap is increasing.

Source: Raabe *et al.* 2022.

5.10 Shares of primary and recycled aluminium since 1950, and projections through 2050



By 2050, the share of scrap in aluminium production will be roughly equivalent to that of primary ore.

Source: IAI 2021.

KEY STEPS TOWARDS
DECARBONIZING ALUMINIUM

Prioritise the use of secondary aluminium and increase scrap recycling

> Using only scrap rather than primary ore could reduce the embodied energy of aluminium by 70 per cent (when considering the processing of scrap) to 90 per cent, a much higher savings potential than for steel or copper (Allwood et al. 2019; Raabe et al. 2022).

> Advanced and machine-learning-assisted scrap sorting and separation techniques can improve the scrap quality by reducing impurities (Raabe et al. 2022).

> Access to scrap will differ among regions, as developed countries have large in-use stocks, while developing countries have to build most of their stocks from primary aluminium (Liu, Bangs and Müller 2013).

Improve material efficiency and design to reduce the demand for primary bauxite ore

> Material efficiency strategies can reduce the total demand for aluminium, therefore increasing the relative share that is produced from scrap.

> Strategies include increasing yields in fabrication and manufacturing, increasing end-of-life recycling, improving the quality of scrap through better sorting, and improving product design (designing for better recyclability and for reduced material use while delivering the same services).

Design aluminium alloys with recycling in mind

> With most aluminium being used in alloyed form, an important pathway towards circularity and lower embodied carbon is designing alloys that are more scrap-tolerant than current alloys.

> For even greater impact, research and development are needed in a new generation of lean alloys that contain fewer impurities and therefore facilitate recycling (Raabe et al. 2022).

Shift aluminium production to renewable electricity sources

> Low-carbon electricity sources are essential for further decarbonizing aluminium production.

> Stark regional differences exist in the electricity mix used for aluminium smelting. In North and South America and Europe, shares of hydropower and other low-carbon sources exceed 75 per cent. Meanwhile, coal dominates in Asia (90 per cent) and Oceania (70 per cent) (IEA 2022c).

Plastics and Polymer Composites

5.5 Plastics and Polymer Composites

KEY MESSAGE

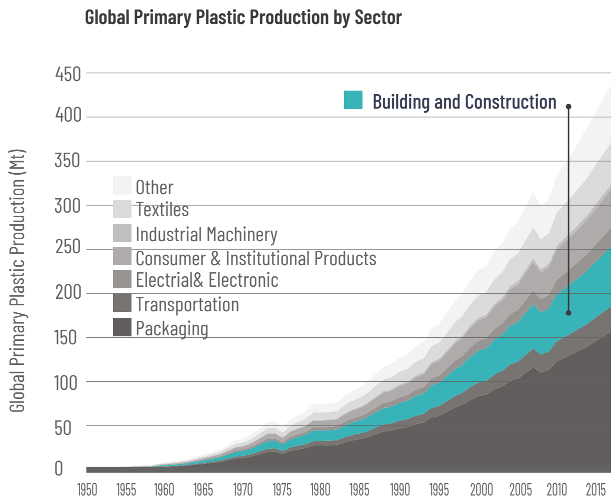
Plastics are everywhere and exist in many grades and even more chemical compositions. While additives optimise the use of plastics in products, they also greatly complicate recycling. Polymers used in buildings as piping or window frames are rarely recycled at their end-of-use.

Use of Plastics in Building Construction Is Increasing Rapidly

Use of plastics and polymer composites is projected to more than double by 2060.

Plastics and polymer composites are ubiquitous materials whose use has skyrocketed since the mid-20th century and is projected to more than double by 2060 (OECD 2022b). Plastics are popular due to the low cost and ease of manufacturing. Plastics production occurs around the world but is expected to grow especially rapidly in Africa, India and the Middle East (see **Figure 5.11**). In the United States of America, buildings and construction accounted for 16 per cent of total plastics use in 2015 (Di et al. 2021). However, this figure does not account for all the plastics used in the interior furnishings and finishes of buildings, which also can pose risks for the health and well-being of inhabitants from material outgassing.

5.11 Total plastics production by region, 1980-2060

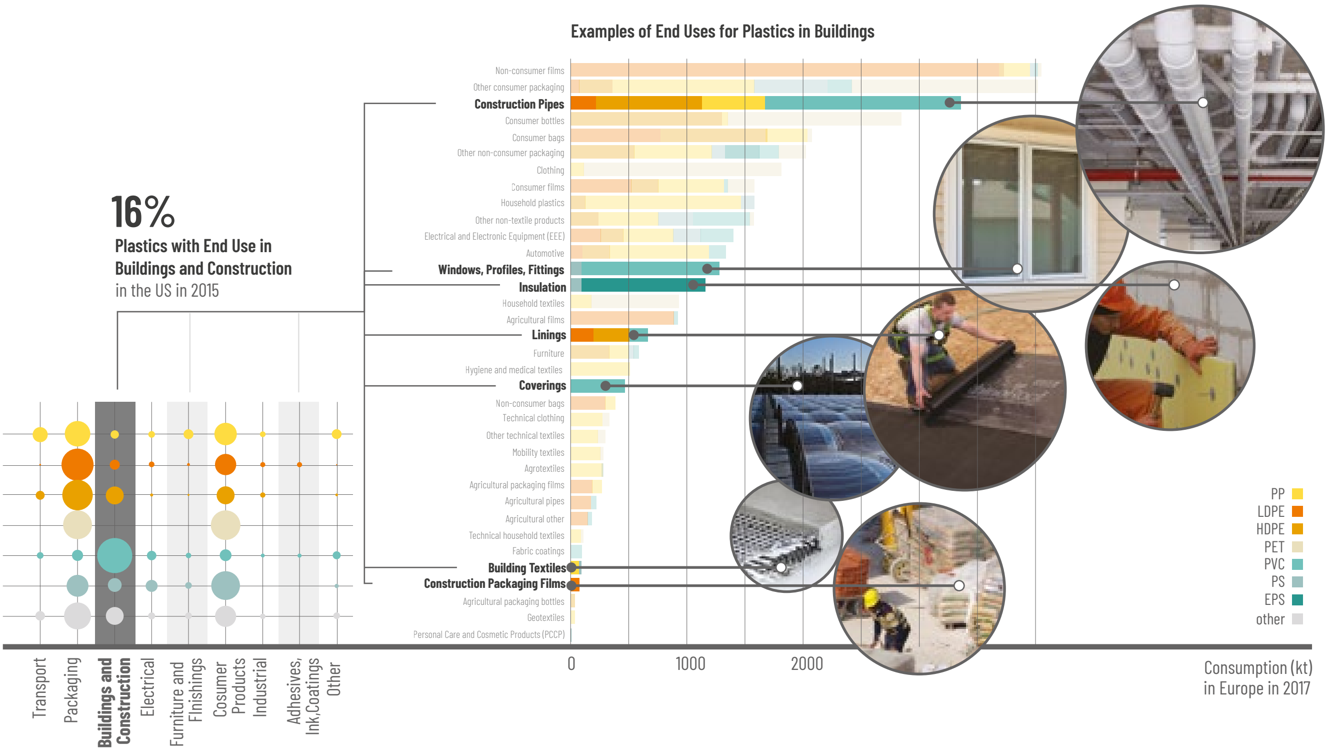


Plastics production is expected to grow rapidly in Africa, India and the Middle East.

Source: OECD 2022b.

5.12 End uses of polymers for the buildings and construction industry

Most plastics are used in the building sector for pipes, windows, insulation, lining and coverings.



Note: The figure shows the mostly widely used plastic polymers in the USA (left) and Europe (right). PP = polypropylene, LDPE = low-density polyethylene; HDPE = high-density polyethylene, PET = polyethylene terephthalate, PVC = polyvinyl chloride, PS = polystyrene, EPS = expanded polystyrene. Source: Di *et al*. 2021; Kawecki, Scheeder and Nowack 2018.

In the U.S. construction sector, the most widely used plastic polymer is PVC (polyvinyl chloride or “vinyl,” used mostly for piping and window frames), followed by high-density polyethylene (HDPE, used in building envelopes) (see **Figure 5.12** left) (Di et al. 2021). In Europe, most of the plastics used in buildings are for pipes (mostly PVC but also HDPE and polypropylene), followed by windows (PVC), insulation (expanded polystyrene), linings, building textiles and packaging films (see **Figure 5.12** right) (Kawecki, Scheeder and Nowack 2018). With a widespread transition to bio-based material composites, the use of polymeric binding agents would increase dramatically. This would require a massive increase in funding for low-carbon polymers that are biocompatible and bio-based.

The Carbon Intensity of Plastics Varies by Type, and Emissions Are Rising

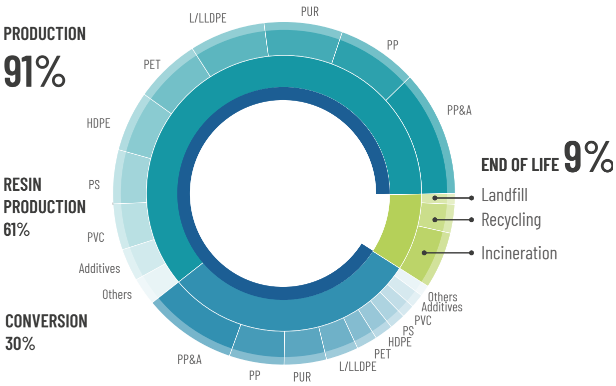
To reduce carbon emissions from plastics requires reducing the growth rate of the sector by half.

Plastics accounted for 3.4 per cent of global greenhouse gas emissions in 2019, and plastics-related emissions are expected to more than double by 2060 (OECD 2022a; OECD 2022b). Around 61 per cent of emissions from plastics are generated during resin production, 30 per cent during conversion processes and 9 per cent during end-of-use processing (see Figure 5.13) (Zheng and Suh 2019). Emissions are lowest during landfilling because plastics do not degrade – and therefore do not contribute to landfill emissions – for many decades. The carbon intensity of plastics varies by type, with the emissions from carbon fibres being four-fold higher than those from the typical resins used (Nicholson et al. 2021).

Large reductions in the carbon impact of plastics are possible through integrated energy, materials, recycling and demand-management strategies to curb life-cycle emissions. One study estimated that to keep plastics-related emissions in 2050 near 2015 levels (thus avoiding the projected four-fold increase) would require major shifts towards bio-based plastics, renewable energy in production, and recycling, as well as reducing the global plastics growth rate from 4 to 2 per cent (Zheng and Suh 2019).

5.13 Life-cycle greenhouse gas emissions from the plastics sector, 2015

The majority of plastics-related emissions are generated during resin production.



Note: The figure shows greenhouse gas emissions by plastic type and life cycle stage. The carbon impact is highest during resin production and lowest during landfilling. PP = polypropylene, LDPE = low-density polyethylene; HDPE = high-density polyethylene, PET = polyethylene terephthalate, PVC = polyvinyl chloride, PS = polystyrene, EPS = expanded polystyrene, PUR = polyurethane, PP&A = polyphthalamide. Source: Zheng and Suh 2019.

Recycling Rates of Plastics Are Very Low and Are Not Projected to Increase Substantially

Globally, the average plastics recycling rate is only around 9%.

Recycling offers an opportunity to reduce the demand for new petroleum-based plastics. Yet the average end-of-life recycling rate is only 9 per cent (Geyer, Jambeck and Law 2017; OECD 2022a), leaving much room for improvement. Plastics' low cost, ease of manufacturing and tunability have resulted in a plethora of chemical compositions that pose technological challenges during recycling. These include concerns about the quality of the feedstock (given the thousands of monomers, additives and processing aids used) (Wiesinger, Wang and Hellweg 2021), colour, contamination and degradation of physical properties. Strict regulations for food-grade applications also limit the use of recycled plastics.

Mechanical recycling is the dominant recycling technology for plastics and entails a series of separation steps, followed by melting and reprocessing. Novel ways to complement mechanical recycling include solvent-based recycling (purification), chemical recycling (depolymerisation, solvolysis) and chemical recovery (thermochemical conversion such as pyrolysis, gasification). However, technologies are highly plastic-specific – requiring strict sorting methods – and industrial implementation and economic and ecological evaluations are mostly pending (Thiounn and Smith 2020; Hofmann et al. 2020).

KEY STEPS TOWARDS

DECARBONIZING PLASTICS AND POLYMERS

Reduce the demand for virgin plastics by increasing recycling and improving collection and sorting

> Recycling plastics offers an opportunity to reduce the demand for petroleum-based plastics. However, plastics recycling faces substantial technological and logistical challenges.

> Better collection and sorting can be encouraged through both market incentives (such as greater recycled content) and regulatory incentives (such as annual increases in recovery targets).

> For windows, collection schemes should focus on the combined recovery of window glass and frame materials (PVC, aluminium, wood) and off-site processing to minimise glass contamination.

Shift from fossil-based to bio-based feedstocks to reduce emissions from plastics

> Bioplastics are either bio-based, biodegradable, or both, with a market share of less than 1 per cent in 2021; only around 50 per cent of bioplastics are biodegradable (European Bioplastics 2022).

> End-of-life management of bio-based, non-biodegradable plastics is of concern since landfilling or incineration would lead to greenhouse gas emissions, negating any upfront carbon sequestration benefits.

> During the transition from fossil-based to bio-based plastics, their combined appearance in recycling streams will further complicate sorting and recycling.

> Misunderstandings about the (bio-)degradability of plastics could lead to an increase rather than decrease of plastics in the environment (Albertsson and Hakkarainen 2017), as bio-degradation depends on controlled industrial composting conditions and would not apply to plastic litter in the environment.

Simplify the chemical compositions of plastics to facilitate greater recycling

> Today's plastics are based on more than 10,000 monomers, additives, and processing aids, with nearly a quarter of them of potential concern (Wiesinger, Wang and Hellweg 2021). Recycling is hindered by the complexity in product compositions and a lack of information on substance properties.

> Designing plastics for the circular economy addresses all life-cycle stages, from circular polymer design (Sobkowicz 2021) to sourcing, manufacturing, use and end-of-use (OECD 2021).

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5.6 Glass

KEY MESSAGE

To reduce the embodied carbon of glass, a set of actions is required. They include shifting energy-intensive glass production to best available technologies and low-carbon energy sources; establishing a policy framework that incentivises flat glass recycling from buildings through local solutions that avoid contamination of recycling streams, and designing glass that minimises unwanted heat absorption into the interior and instead captures solar energy for heating, cooling and lighting.

Demand for Glass in Construction and Renovation Is Rising

The buildings sector is the second largest end user of glass after packaging.

The glass sector is divided into flat glass (51 per cent; for buildings, automotive and electronics), container glass (45 per cent; for food and beverages) and other glass (4 per cent; e.g., domestic glass and tableware) (International Year of Glass [IYOG] 2020). The buildings sector accounts for around two-thirds of flat glass production, with glass used in most building façades as well as in many interior applications. Around 60 per cent of the world's flat glass manufacturing capacity is in China (IYOG 2020).

Glass is Energy Intensive to Produce and Involves Emissions Trade-offs

Multi-paned windows save energy during operations but are more energy-intensive to produce.

Glass production is a high-temperature (between 1,400 and 1,600 degrees Celsius), energy-intensive process that is responsible for 0.3 per cent of global carbon emissions (86 million metric tons) (Westbroek et al. 2021). Glass production reached 209 million metric tons in 2019 and is growing rapidly at 5.2 per cent annually (IYOG 2020). The raw materials for virgin glass production are sand, lime or calcium carbonate, and soda ash. Mining these materials poses a high risk of forced labour (Grace Farms Foundation 2022). Melting the raw materials for glass leads to two main sources of CO_2 emissions: 1) energy emissions from melting and 2) process emissions from adding limestone and soda ash to the melt (Westbroek et al. 2021). The energy intensity of production depends greatly on the technology and fuel source used.

Glass is among the most controversial building materials, with trade-offs between embodied and operational emissions. High-efficiency windows with double or triple panes provide substantial energy savings during the operation of buildings but are more energy intensive to produce. Glass coatings reduce operational emissions by providing shading and reducing the need for artificial lighting (Arup and Saint-Gobain Glass 2022), but they complicate recycling with their complex material composition. Variations in design and expected building lifetimes greatly influence emissions over the glass life-cycle.

At the manufacturing and use phases, the most promising measures for improving the material efficiency of glass (and thus reducing emissions) are the re-use of container glass (68 per cent re-use brings emission savings of 38 per cent), using less material in the design of containers (10 per cent reduction in mass brings 6 per cent emission savings) and extending the lifespans of buildings and vehicles (Westbroek et al. 2021).

Hardly Any Glass in the Built Environment Is Recycled

Recycling is a powerful but underused tool for decarbonizing glass, particularly in the buildings sector.

Glass is a material that in theory could be produced in a low-carbon manner and be infinitely recyclable. In practice, only a third of container glass and hardly any flat glass is recycled. Container glass, used mostly for beverages, typically faces short lifetimes (less than one year) and has well-established recycling technologies; its average recycling rate is 32 per cent globally, although in some countries it reaches 70 per cent (Westbroek et al. 2021). In contrast, flat glass is used mainly for buildings with long lifetimes, estimated at 75 years, delaying recycling opportunities (Westbroek et al. 2021).

The little glass from the built environment that is recycled is rarely recycled as flat glass; instead, after removal it is downcycled for use in insulation, containers, construction aggregates and road paint, among others (Westbroek et al. 2021). In Europe, the recycled content of flat glass is 26 per cent, but most of it comes from pre-consumer scrap (Glass for Europe 2020), as post-consumer material currently cannot reliably meet the strict quality requirements in flat glass manufacturing. Also, the high weight-to-volume ratio of glass makes its transport costly, with high environmental impacts; for this reason, it is important to set up local and regional recycling infrastructures (Bristogianni and Oikonomopoulu 2022).

KEY STEPS TOWARDS

DECARBONIZING GLASS

Shift glass production to low-carbon energy sources and best available technologies

> Solutions include switching to low-carbon fuels, melting using renewable electricity, improving energy efficiency in processing and operations, and waste heat recovery (Zier et al. 2021).

> Analysis of 16 emerging glass production technologies showed potential energy savings of 20-70 per cent (Springer and Hasanbeigi 2017).

> Large regional differences in emissions indicate that a shift to best available (and emerging) technologies is a key decarbonisation tool (Scalet et al. 2013).

Provide incentives for local production and recycling

> Using recycled glass ("cullet") in glass manufacturing can reduce energy use in furnaces by 2.5 to 3 per cent for every 10 per cent of cullet input, on top of the savings from avoided soda use (IEA 2007) (or 30 per cent if all glass were manufactured from cullet).

> Through the proper handling and recycling of building glass, the European Union could avoid the landfilling of 925,000 metric tons of glass waste annually and save around 1.23 million metric tons of primary non-renewable raw materials (Hestin, de Veron and Burgos 2016).

> These measures require education and close collaboration of contractors and recyclers, standards and legislation that encourage such practices (e.g., landfill tax, incentives for locally based production and recycling), rewards for recycling and re-use in certification systems, and focusing sustainability assessment credit systems (e.g., BREEAM, LEED) on the re-use and recycling of glass.

Improve glass renovation and demolition practices to maintain quality and enable recycling

> Increasing the use of flat glass cullet requires ensuring that the recycled glass is clean, with only minimal contamination (e.g., no mixing in of special heat and fire-resistant glass types like Ceran).

> Discarded windows should be disassembled off-site in clean environments that allow for efficient separation and for closed-loop recycling processes that maintain the high quality of flat glass and the re-use of coated glass where possible (Glass for Europe 2013).

> Glass recycling needs to be optimised for the local context, balancing the needs for high collection efficiencies and material quality (Hestin, de Veron and Burgos 2016).

> An alternative glass recycling path proposes the local, low-tech and contamination-tolerant casting of cullet into voluminous cast glass components for structural applications in architecture and interior design (Bristogianni and Oikonomopoulu 2022).

Improve glass design and related components by adopting best available technologies

> Typically, glass is not used on its own in buildings but is associated with a range of other materials and components. The supply chains for glass curtain walls in particular can be complex.

> Decisions made during the design stage can have impacts on the embodied carbon of glass systems. Incentives in education and enforcement by building codes would greatly increase the availability of circular glass.

> In commercial buildings, use bio-based framing materials, such as engineered timber or bamboo, rather than high-carbon materials such as aluminium.

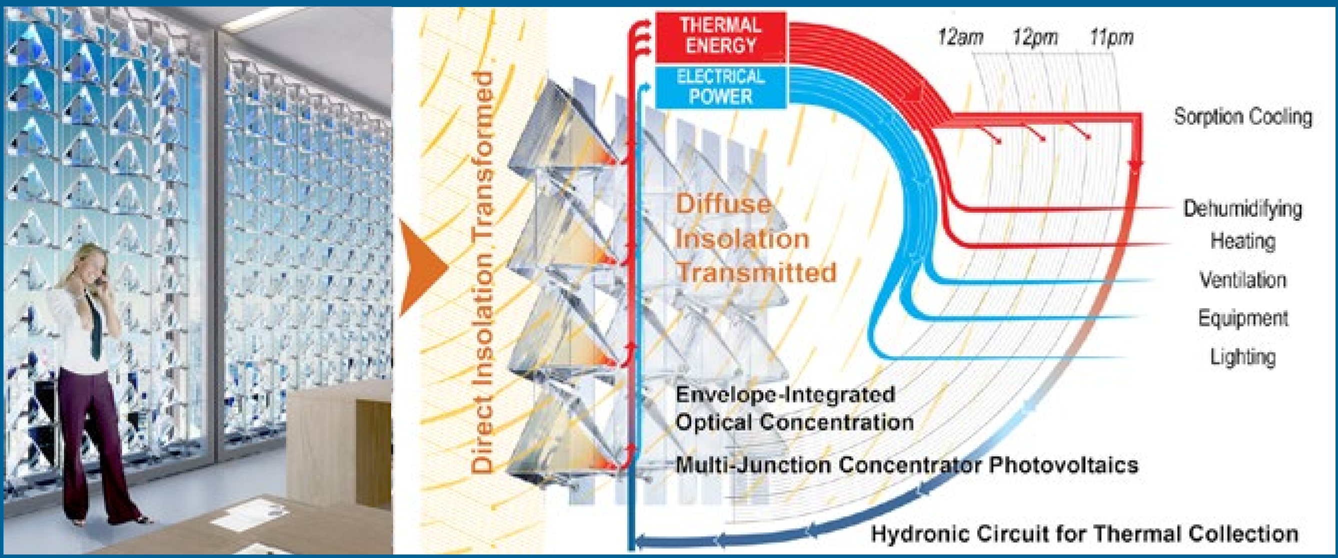
Improve glass design for windows and curtain walls to optimally absorb, store and redistribute solar energy for building functions

> Glass façades often drive up the energy demand for cooling Glass façades often drive up the energy demand for cooling because they either let in too much heat and glare (increasing the size and emissions of cooling equipment) or they reflect the excess solar energy onto urban pavements, worsening the heat island effect and driving up cooling loads.

> By using building information modelling in the design phase, a building's shape and façade can be designed to let in more solar energy during cold periods and remain self-shaded during hot periods. However, these strategies are limited in hot climates.

> Far more research and development is needed to adapt glass façades to capture solar energy for use in heating, cooling, lighting and electrical loads in the building interior (see **Figure 5.14**). Glass is key to the future on-site solar collection technologies that can enable net zero buildings (Novelli et al. 2022).

5.14 Advanced glass façades



Glass façades of the future need to capture solar energy for use in heating, cooling, lighting and electrical loads. Due to its transparency and durability, glass has a unique relationship to the energy balance of buildings: it can transmit up to 80% of available natural daylight, thereby greatly boosting the health and wellbeing of occupants, while lowering electrical loads, it has also been implicated in driving up the cooling expenditures of building through unwanted solar heat gain. (although this would generally be a net positive in cold climates in the winter).

In future, in order to reach net-zero operational energy, per the figure below, glass will be a very important material for combining the collection of sunlight for both daylighting, heating cooling and electricity, in order to optimise for all of these functions simultaneously.

Source: Novelli *et al*. 2022.

Masonry and Earth-Based Materials

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5.7 Masonry and Earth-Based Materials

KEY MESSAGE

Important progress is occurring in the decarbonisation of earth-based masonry, including through the use of low-carbon binders, secondary cementitious materials and admixtures that result in higher-quality products. However, scaling the adoption of these materials affordably relies on local adoption of existing standards, certification (low-carbon credits) and coordinated upskilling of stakeholders.

Decarbonisation of the buildings and construction sector requires a shift away from the use of conventional high-carbon, non-renewable building materials and towards the use of renewable and bio-based materials. However, it is unrealistic to assume that the sector can rapidly and easily transition to 100 per cent renewable biomaterials. During the interim period and beyond, it is critical to support the continued use of lower-carbon non-renewable materials such as masonry and earth-based materials.

Traditional Technologies Have Proven Benefits but Have Lost Appeal in Emerging Markets

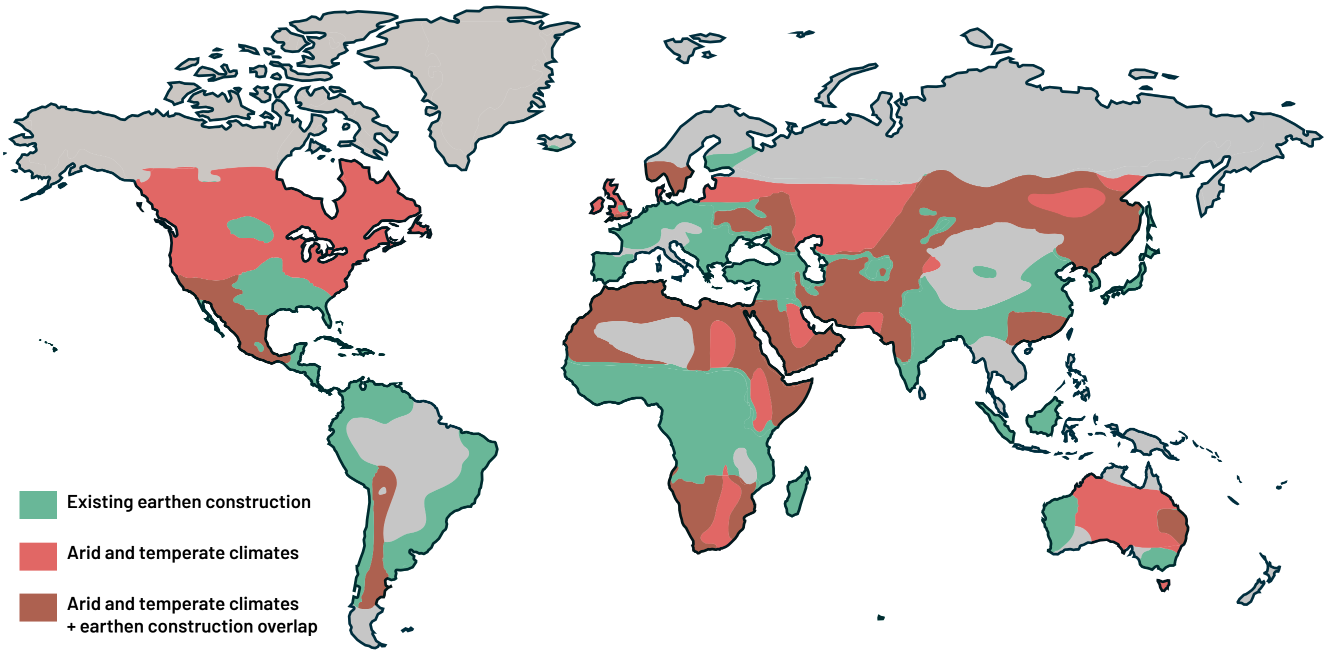
For much of human history, people have used earth-based materials for load-bearing applications in masonry construction, with sustainable, low-carbon methods. In the traditional context, these materials are made on-site by mixing clay-rich soil, natural fibres, and water, and letting them dry in high outdoor temperatures. Recycling of non-fired earth-based materials is common practice, as the clay binders can be re-used without additional heating or chemical treatment.

Due to their high thermal mass, earth-based materials can have positive benefits for passive space conditioning, greatly reducing the operational carbon of buildings in certain regions, particularly arid climates (see **Figure 5.15**). Given the projected impacts of climate change in regions characterised by extremely high day temperatures (above 40 degrees Celsius) and cold nights, passive earth-based systems could help mediate harsh climatic patterns.

Only around 8-10% of the world's people currently live in earth-based structures.

At the end of the 20th century, earth-based structures housed around a third of the global population; since then, this share has fallen to only 8-10 per cent, with 20-25 per cent of the use occurring in developing countries (Houben and Guillaud 1994; Marsh and Kulshreshtha 2022). As incomes have risen and access to concrete masonry has increased, the use of earth

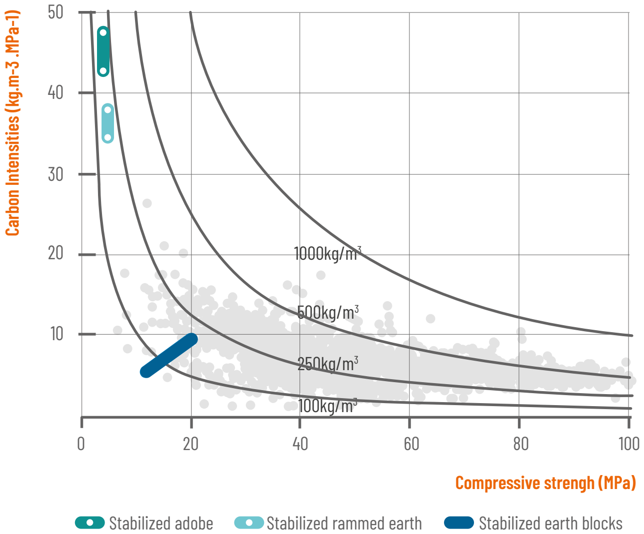
5.15 Climate types and the potential for earth-based buildings



Earth-based buildings have high potential to reduce emissions in arid and temperate climates.

Note: The figure shows the climate types where earth-based buildings have potential to drive down operational carbon through effective passive design.
Source: Gupta 2019.

5.16 Comparison of the carbon intensity and mechanical performance of different stabilised earth masonry technologies



Stabilisation of earth masonry using Portland cement multiplies the carbon intensity index.

Source: Adapted from Van Damme and Houben 2018.

as a building material has declined. Countries where more than 10 per cent of the population still lives in earth-based buildings include Bangladesh, the Democratic Republic of the Congo, Ethiopia, India, Mexico, Nigeria, United Republic of Tanzania and Viet Nam (Marsh and Kulshreshtha 2022).

In many developing countries, earth-based masonry is associated with poor durability, poor moisture performance, high maintenance and low social class. Inappropriate use of the material for the local context has influenced perceptions. Poor building orientation, large west-wall surface areas and poor cross-ventilation can bring inefficiencies in heat gain/loss. However, across regions, and within high-end architectural design, there is renewed interest in innovating earth-based practices with contemporary techniques and standards.

Earth brick production can be very low carbon, but it is at risk for poor on-site labour and environmental conditions.

Although the potential is high to increase development of locally based supply chains, the production of earth-based materials can have negative social impacts if not properly overseen. Brick is one of the most-used materials at risk for forced labour, with more than 20 countries identified for abuses within the industry (Grace Farms Foundation 2022). Children and adults producing bricks are often held in debt bondage and breathe hazardous dust for prolonged periods.

BOX 5.3

GREENING THE MASONRY VALUE CHAIN IN WEST AFRICA

With their young populations and growing need for infrastructure and housing, developing countries in Africa represent the future in concrete masonry demand. West Africa has traditionally imported most of the clinker and cement that it uses for concrete production, due to the lack of suitable limestone reserves. Given the high carbon footprint of concrete masonry structures that rely on Portland cement binders, however, the development and adoption of local, low-carbon alternatives is key.

Ghana has the highest use of Portland cement in sub-Saharan Africa, at 215 kilograms per person (Harder 2021). Across West Africa, reducing import dependence through substitution of Portland cement with earth-based, locally available cementitious materials and pozzolana resources will be key to driving down CO_2 emissions and increasing economic resilience (Bediako, Amankwah and Adobor 2015). Already, leading cement companies in Ghana, such as SUPACEM and Pozzomix Cement, are using calcined clay cement as an alternative to clinker-based cement.

Adobe earth masonry technologies have a long history in West Africa. They are traditionally made from ubiquitous laterite soils comprising sand, clay, silt, and pebbles, sometimes mixed with cow dung or fibre from guinea grass straw. The modern version of adobe is the compressed earth brick, produced using chemical stabilisation and compaction to improve mechanical performance. Earth masonry is based on community-specific knowledge as well as small-scale industrial manufacturing of stabilised earth block products.

For countries that supply West Africa with cement, such as Senegal, using low-carbon fuels in production and integrating earth-based masonry products into the value chain is critical. One of Senegal's largest cement companies, Sococim, is using alternative fuels such as groundnut hulls. Senegal is also experimenting with using Typha aquatic weed biomass to develop earth masonry walls and roofing products on-site (see **Figure 5.17**).

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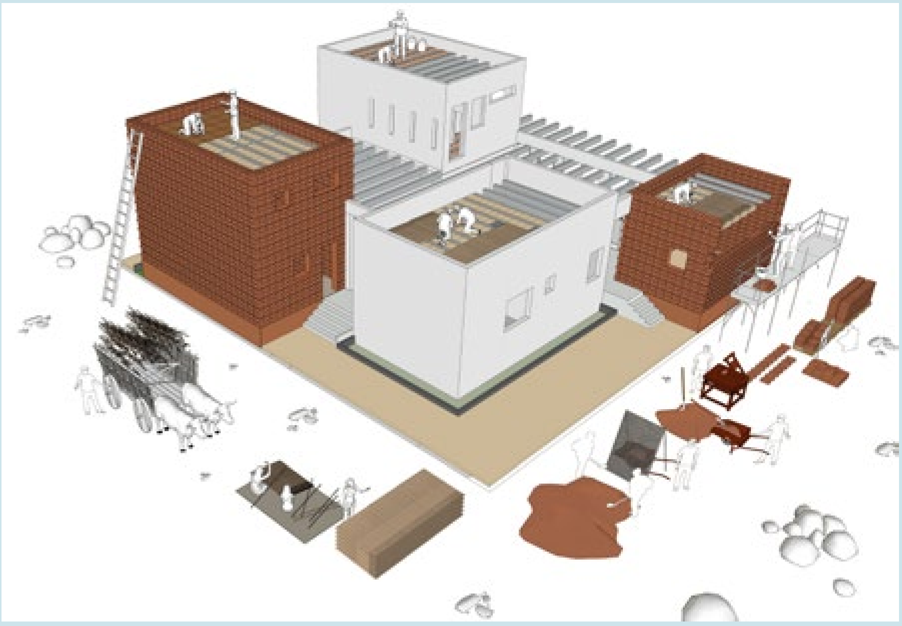
5.17 Compressed earth block masonry wall and on-site manufacturing in Dakar, Senegal



Senegal is experimenting with Typha weed biomass to develop earth-based structures.

Credit: Worofila.

Emissions from Earth-Based Technologies Rise with Cement-Based Mortars

To improve the performance and durability of earth masonry, progress has been made in developing low-carbon binders, surface treatments and admixtures (chemicals used to reduce binder and water demand and increase durability) (Van Damme and Houben 2018). Traditionally, material stabilisation has been achieved using earthen plasters and stuccoes that integrate a range of plant-based resins, gums, plant juice, animal dung and fluids. More recently, the use of Portland cement to stabilise earth blocks greatly drives up emissions, with only minor performance benefits that can also be achieved through low-carbon, circular by-products (see **Figure 5.16**). Thus, the carbon footprint of earth-based building technologies varies depending on the binders, natural fibres and additives used; on where production occurs (on- or off-site); and on the use of compaction or firing to improve material strength and durability.

> For non-fired adobe earth blocks that cure in the sun (made from sand, clay binder and organic material), the embodied carbon can range between 1.2 and 5.4 kilograms of CO_2 per kilogram of earth block (Illampas, Ioannou and Charmpis 2014; Christoforou *et al.* 2016).

> For fired clay bricks, the carbon footprint skyrockets due to the high temperatures required for clay sintering. When using a natural gas-fired kiln, the average carbon footprint is an estimated 230-250 kilograms of CO_2 per kilogram of earth block (Kulkarni and Rao 2016). The footprint using an oil-fired kiln is 1.4 times higher, near 340 kilograms of CO_2 per kilogram of earth block (Venta and Eng 1998).

> For rammed earth wall structures – in which processed earth soil is compacted into solid walls using temporary formwork – the use of Portland cement stabilisers and electric and pneumatic ramming can greatly increase carbon footprints (Reddy and Kumar 2010). Compared to conventional concrete masonry, adding 5-10 per cent Portland cement and lime to rammed earth structures led to higher CO_2 emissions and worse performance (Scrivener, John and Gartner 2018). The carbon footprint of stabilisation techniques must be weighed against the susceptibility of unstabilised earth walls to mechanical and moisture damage and erosion.

Interest in Modern Earth-Based Construction Is Gradually Increasing

The stock of modern earthen buildings is growing.

Due to the high quality and appeal of modern earthen buildings, the use of local earth resources for building is gaining recognition as a "niche," reliable and attractive option (Swan, Rteil and Lovegrove 2011; Niroumand et al. 2017). As a consequence, the number of innovative earth-based products from earth construction companies has increased (Leylavergne 2012; Marsh and Kulshreshtha 2022), as has the worldwide stock of modern earthen buildings (Correia, Dipasquale and Mecca 2011). However, such initiatives are limited by the high costs of entrepreneurial experimentation and early adoption shouldered by clients.

KEY STEPS TOWARDS

DECARBONIZING EARTH-BASED MASONRY

Improve the design of earth-based masonry for longevity, and provide technical training

> In the near term, effort is needed towards improving the longevity of earth masonry without Portland cement (Scrivener, John and Gartner 2018).

> Technical training is needed on the design to enhance the durability of earth masonry and panel systems.

> On-site training and upskilling of architecture, engineering and construction professionals is needed to encourage and normalise the design and integration of earth-based technologies.

Shift from Portland cement binders to low-carbon alternatives in earth-based masonry

> Rapid development is needed of low-carbon binders, natural supplementary cementitious materials.

> Promote alternatives to Portland cement for binders, such as low-carbon lime, alkaline-activated materials, and geopolymers, including volcanic pozzolan (Abid et al. 2022; Kamwa et al. 2022).

> Promote bio-based supplementary cementitious materials including fused laterite and agricultural and industrial residues, often available locally (Adinkrah-Appiah and Obour 2017; Schmidt et al. 2021).

> In developing countries where low-carbon binders and cementitious supplements already exist, incentives and education are needed to stimulate market demand and financing to scale adoption (see **Box 5.3**).

Develop locally adapted standards to increase adoption and affordability of earth-based masonry

> Incentivise stakeholders to continue to develop regional and international standards for earth-based materials that can be integrated into local and regional building codes and material standards (CRAterre-EAG 1998; New Zealand Standards 1998; Vyncke, Kupers and Denies 2018; Africa Research and Standards Organisation 2018; Schroeder 2018).

Increase education and demonstration to boost societal and industry acceptance of earth buildings

> Incentivise professionals to develop awareness among clients and to build the research capacity to address negative perceptions and technical challenges.

> To incentivise the adoption of low-carbon, earth-based materials, education on their positive impacts needs to be extended to building owners as well as finance and insurance companies.

> Education on the appropriate design and integration of earth-based materials is critical for improving furability and reducing operational carbon, especially for housing in tropical rainforest and savanna climates.

TABLE 5.1

SUMMARY OF DECARBONISATION STRATEGIES PER MATERIAL

NON-RENEWABLE MATERIALS

- Improve quarry rehabilitation and biodiversity restoration of landscapes.
- Reduce the clinker-to-cement ratio with alternative materials.
- Use recycled aggregates.
- Electrify kilns and use renewable electricity sources.
- Integrate carbon capture and storage to provide additional strength.
- Minimize waste with computational design-for-disassembly and re-use.
- Minimize on-site waste and emissions through pre-fabrication.
- Educate building design professionals in material efficiency, optimization.
- Develop standards and building codes that require modular concrete.
- Incentivize renovation over demolition and building codes for recycled.

- Shift from blast furnaces to direct reduced iron (DRI) technology.
- Electrify all steel production methods with renewable energy sources.
- Reduce steel use through a combination of material efficiency measures.
- Avoid using new steel by substituting with re-used (best) and recycled materials.
- Shift to low-carbon alternatives such as bio-based materials if possible.
- Adapt building codes to avoid overspecification and optimize structures.
- Design with pre-fabricated elements for disassembly and re-use.
- Include material efficiency training in the curricula of architects and engineers.
- Ensure that stakeholders across the value chain use the same metrics.
- Improve recycling methods to enable the recovery and use of more steel.

- Reduce demand for new aluminium by promoting re-use and recycling.
- Use electricity from renewable sources (including hydropower).
- Impose strict regulations to design for the circularity of component parts.
- Standardize aluminum alloys/components for re-use.
- Avoid overspecification and use of primary source material.
- Electrify heavy construction and transport equipment.
- Specify high-performance building envelopes.
- Maximize recycling and invest in alloy-specific sorting and recycling.
- Certify disassembled and re-used components.

- Avoid the production of non-recyclable products that harm the biosphere.
- Reduce the use of plastics in building materials, where feasible.
- Use bio-based and bio-degradable plastics produced with renewable energy.
- Design for disassembly and re-use.
- Standardize the chemical compositions of polymers for ease of recycling.
- Increase transparency and/or standardize chemical compositions.
- Trace material usage to keep track of available stock.
- Increase material life with low-carbon maintenance practices.
- Invest in much greater collection, sorting, and mechanical recycling to avoid production of new plastic, complimented by improved chemical recycling.

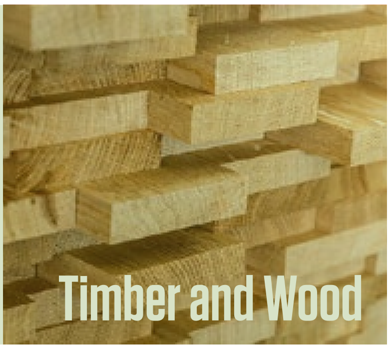
- Avoid new demand by extending lifetimes of buildings and components.
- Incentivize and support locally produced and recycled glass sources.
- Improve research on efficient melting techniques to avoid emissions.
- Shift glass production to best available technologies and recycling.
- Electrify production, construction, and transport with renewable energy.
- Use process intensification and waste heat recovery.
- Design standard components and façade surfacing for recycling, re-use.
- Design glass façades that minimize heat absorption and reflection and instead capture solar energy for heating, cooling, water and lighting.

TRANSITIONAL

- Regulate quarry closure to restore natural landscapes.
- Use structural and facing brick to increase longevity and reduce maintenance.
- Replace high-carbon cement binders with lower-carbon alternative binders.
- Use cement/mortar alternatives, such as fly ash waste and sewage sludge ash.
- Design masonry units for disassembly and re-use.
- Incentivize local, low-carbon earth masonry making.
- Educate design professionals in methods to enhance the longevity of non-stabilized earth masonry.
- Incentivize renovation over demolition.

RENEWABLE MATERIALS

- Incentivize forestlands owners to develop sustainable management and biodiversity.
- Improve the design of forest byproducts, to improve circularity in timber.
- Improve collection rates of "clear-cuts" from logging practices and off-cuts from wood manufacturing for wood products.
- Improve wood manufacturing to capture loss from timber processing.
- Promote and incentivize the use and re-use of structural mass timber.
- Train and upskill construction actors in design-for-disassembly wood.
- Update building codes to mandate reliably certified products.
- Incentivize the research and development of non-toxic glues and binders.



- Increase policy support for commercial enterprises transitioning to highly productive and sustainable bamboo forest management.
- Improve bamboo plant propagation methods.
- Transition bamboo manufacturing to on-site renewable energy.
- Promote material efficiency by developing structural standards for different regional species and circular design.
- Incentivize the use of non-toxic chemicals and glues.
- Integrate and/or adapt bamboo standards for local building codes.
- Educate architecture, engineering and construction professionals.

- Integrate intersectoral biodiverse biomass supply chain management.
- Incentivize and invest in technologies and bioadhesives.
- Redirect biomass towards higher-value end-of-use products.
- Create financial incentives for the capture of biomass building materials.
- Educate and train built environment professionals in design.
- Educate stakeholders on effective maintenance of products.
- Educate finance and insurance companies to incentivize adoption.
- Implement marketing and education programmes.
- Train and upskill material recovery management to improve re-use rates.

- Understand native ecological systems and context before introducing new living biomass material; Use native species and organic fertilizer.
- Adapt district-scale carbon incentives for impacts to urban heat island and stormwater infrastructure.
- Design with low-carbon material substructures, growing media, passive solar energy, and harvested rainwater for irrigation.
- Provide avenues for circular compost and waste by-product recovery.
- Minimize material use through the optimization of structures.
- Minimize weight of materials by using less water and soil.

6

TOOLS for Assessing Carbon Impact Across the Building Life Cycle

Tools are emerging that enable verification and tracking of material, energy and information flows across the building life cycle.

6.1 Measurement and Data are Improving, but Transparency and Verification are Needed

The use of readily available tools to manage, visualize and communicate the data behind decisions can be game-changing.

Coming together to construct sustainable buildings and cities is hard work. Shifting the process towards bio-based and circular renewable materials makes it even more challenging. The use of readily available tools to manage, visualise and communicate the data behind decisions can be game-changing. In formal construction, where supply chains for building materials and systems are highly complex, computational tools and data visualisation frameworks are key in helping decision-makers compare the pros and cons of different materials in terms of their embodied, operational and end-of-use emissions. However, huge discrepancies in access to such tools exist across the formal to informal construction sectors.

To comply with increasingly ambitious emission reduction goals and pledges, stakeholders across the built environment sector are taking responsibility for a wider scope of information, in order to deliver materials and systems that have predictable and verifiable environmental performance. Data management and visualisation tools are emerging that offer "at-a-glance" scenarios to support decision-making in real time. However, as with environmental assessments and certifications across all sectors, the verifiability of data remains a huge challenge. There is a significant range in the quality and quantity of transparent data, regulatory procedures, and certification processes across all material sectors, even the most developed ones, resulting in uncertainty on the part of material specifiers.

The transparent measurement and quality of data on the environmental impacts of construction materials continues to improve. Accessible and transparent tools are emerging that involve third-party verification and tracking of global material, energy and information flows across the building life cycle, providing the policy enablers for market transformation. However, considerable challenges remain in comparing the environmental impacts of materials and systems through the use of third-party certifications, due to variability in data quality, methods, functional equivalencies, etc. (see **Figure 6.1**).

6.1 Municipal building energy codes need to transition to include embodied energy

Various requirements and challenges are necessary for such a transition.

Adapted from American Council for an Energy-Efficient Economy 2021.

Table 6.1

TOOLS AND STANDARDS USED TO ASSESS LIFE-CYCLE EMISSIONS

Life-Cycle Assessment	Life-cycle assessment refers to a systematic analysis and evaluation of the potential environmental impacts of material products or services during their entire life cycle, from production to distribution, operation and end-of-life (or use) phases. In 2006, the International Organisation for Standardisation (ISO) issued two revised standards for life-cycle assessment – ISO 14040 and 14044 – that set out a four-stage assessment process: 1) goal definition and scoping (ideally including all direct and indirect sources of emissions throughout the life cycle), 2) life-cycle inventory (collecting data on all the system inflows and outflows), 3) impact assessment (classifying these flows into environmental impact categories and characterising them by their impact potential) and 4) interpretation (ISO 2006a; ISO 2006b).
GHG Protocol	The Greenhouse Gas (GHG) Protocol, founded in 1997, aims to establish a set of clear, rigorous and consistent accounting rules to calculate the "carbon footprint" of products. The initiative introduced a three-fold categorisation of life-cycle greenhouse gas emissions: scope 1 (direct emissions from own facilities and vehicles), scope 2 (indirect emissions from purchased electricity and fuels) and scope 3 (emissions from all other upstream and downstream activities). Of special interest to the built environment sector are software tools that help calculate the greenhouse gas emissions of specific sub-sectors and materials, including aluminium, cement, iron and steel, and wood. Importantly, the GHG Protocol also includes several complementary standards for the calculation and management of emissions at different scales, from products to the corporate level to whole cities.
Environmental Product Declarations	Environmental product declarations are one of three types of environmental labels established under ISO 14020 standards for ecological labelling, designed to help businesses measure and communicate their efforts to minimise their environmental impact (ISO 2006c; ISO 2016; ISO 2018; ISO 2022b). Of the three label categories – certified eco-labels, product self-declarations and environmental product declarations – only the latter mandates the use of life-cycle assessment to quantitatively estimate life-cycle impacts, including greenhouse gas emissions. In 2012, the European Committee for Standardisation (CEN) published standard EN 15804 to regulate how life-cycle assessments are applied to environmental product declarations in the construction sector (CEN 2019). However, concerns remain among stakeholders regarding the limited transparency and access to development processes for environmental product declarations (Gelowitz and McArthur 2016).
Product Environmental Footprint (PEF) and Organization Environmental Footprint (OEF)	Since 2012, the European Commission has been developing an ambitious scheme aimed at providing detailed guidance for calculating the "environmental footprint" of a product and organisation (European Commission Joint Research Centre n.d.). While based on life-cycle assessment, these efforts aim to improve consistency and comparability by mandating specific choices in terms of system boundary, allocation procedures, impact assessment methods, etc. One notable innovation is the use of a "circular footprint formula" to enable the consistent calculation of end-of-life recycling credits across all life-cycle assessments that are compliant with the PEF.* Development of the PEF methodology is still in progress, but it has already resulted in at least one mandatory standard: the 2019 revision of EN 16804+A2 for the European construction sector (CEN 2019) with a more rigorous accounting of biogenic carbon flows.

* A detailed discussion of the methodological implications of this formula is beyond the scope of this report, but it is essentially a case of establishing an agreed-upon compromise rather than correcting or improving upon the previously existing alternative methodological options.

The challenge across all global sectors, from informal to formal construction, is to get the right data to the right stakeholders at the consequential stages of decision-making. Even in the most enhanced built environment processes, certifications such as full life-cycle assessment are too cumbersome to conduct at the critical initial stages of planning. Often, material choices and systems are set in motion due to socio-economic or cultural pressures and are difficult to shift once a multi-stakeholder process is established.

6.2 Existing Tools for Assessing Carbon Impact

Decision-makers need easier access to the right data to assess the carbon impacts of their material choices.

For decision-makers to adopt and apply whole life-cycle thinking and make optimal decisions about decarbonisation, they must have access to the right data to assess the carbon impacts of their material choices. Rigorous estimation of the "carbon impact" of building materials across the building life cycle is not an easy or trivial task, and in the past significant expertise and time were required to make proper life-cycle assessments (Takano et al. 2014).

Current efforts are improving the accessibility of this task through the use of "at a glance" tools. Analysts now have key tools to draw from, developed during three decades of methodological refinement, as well as a series of detailed and pragmatic sector-specific standards and guidelines. These tools attempt to solve the problem of producing consistent results that can be meaningfully compared across studies. However, further development is required to address variability in data provenance and reliability. **Table 6.1** provides a summary of some of the most common tools for assessing life-cycle emissions.

6.3 Recommendations for Future Carbon Assessment Tools

Emerging tools can provide non-experts such as designers and developers with snapshots on data associated with different decisions; however, they are still at an early stage and require more development. The key to supporting productive use of these tools is for them to provide more transparency and third-party analysis and qualifications to the data.

Disseminating Data and Low-Carbon Methods in Semi-formal and Informal Construction

Adding data on the effects of materials on operational energy costs could be a key incentive towards shifting consumer patterns.

Access to carbon assessment tools is deeply uneven across sectors and regions, necessitating alternative ways to communicate the carbon impacts of material choices to more stakeholders. Although most of the construction boom in developing countries is taking place without the regulation of building energy codes, in a world of smartphones, many inhabitants across the spectrum of housing types (formal, semi-formal, informal) are keeping a close eye on their energy and water bills. Therefore, adding data detailing the effects of materials on operational energy costs such as heating, cooling and air-conditioning could be a key incentive towards shifting consumer patterns, as building occupants begin to understand how to lower their energy bills by simply choosing the right roofing or cladding materials.

For example, conventional building materials – including the concrete and asphalt often used in roofing – absorb solar radiation and emit heat, causing temperatures to increase and cooling loads to soar (Doulos, Santamouris and Livada 2004; Prado and Fereira 2005; Bozdogan Sert et al. 2021; Stache et al. 2022). As informal housing rapidly increases in density, with do-it-yourself additions and upgrades, adding simple data to utility bills supports building occupants to make decisions on additions and renovations using low-cost bio-based materials that lower their energy bills while improving thermal comfort.

Creating Data and Knowledge-Sharing Networks Among Stakeholders

Future tools need to be interoperable and to communicate impacts across the life cycle.

Perhaps the biggest impediment facing building professionals who do have full access to the latest software is that there are so many different tools available, and experts need to be speaking to each other (Aly Etman et al. 2016; Aly Etman, Keena and Dyson 2017; Keena 2017; Keena and Dyson 2017; Keena, Aly Etman and Dyson 2020). The compartmentalisation and lack of communication among building professionals in each sector results in sub-optimal material designs that contribute to environmental impacts across the life cycle (U.S. Department of Energy 2008; Du Plessis and Cole 2011).

A McKinsey report reinforces the stagnant productivity numbers in the construction sector and predicts that, faced with sustainability demands, the sector will need to reassess digital methods to reduce waste and abate carbon emissions (Barbosa, Woetzel and Mischke 2017). The report highlights the role that "big data" can play in helping to establish collaborative networks, with efficient construction practices that track material, energy and information flows across the building life cycle. In the construction phase alone, on-site productivity could increase by 50 per cent based on the implementation of data techniques and accurate data flows through stakeholder systems that are both backward-looking (tracing back to production phase) and predictive (modelling

BOX 6.1

DATA HOMEBASE: A WEB APPLICATION VISUALISING CANADA'S HOUSING CHARACTERISTICS TO FOSTER A CIRCULAR ECONOMY

Like many countries worldwide, Canada is facing a housing crisis. One approach to tackling housing supply is through the circular economy, by keeping materials and buildings in use for as long as possible to reduce waste and promote sustainability, and by re-using building materials rather than turning them into waste. However, effective circular economy decision-making requires robust data on buildings, and in most cases these data are widely scattered and lack standardisation.

To overcome this barrier, an interdisciplinary team led by researchers at McGill University has developed "housing passports," or standardised digital descriptions of residential building characteristics. Each housing passport represents different residential typologies based on analysis of the existing building stock. Through a new web-based, data visualisation application called Data Homebase, housing passport information is organised, linked and visualised in a manner that makes it easily accessible to a wide variety of housing stakeholders, from the building sector to finance and policy making. For example, housing passports can help banks complete property assessments and help cities manage government housing assets.

Data Homebase integrates and annotates data, displaying calculations of estimated energy use, carbon emissions and affordability indexes of residential buildings across Canadian cities. It does this at multiple scales: the city scale, the neighbourhood scale and the building materials scale. By providing a comprehensive display of a building's degree of circularity across these scales, the app allows stakeholders to detect which buildings at the city and neighbourhood level, and what aspects of an individual building, are primed for improvement, from retrofit to material recovery. Stakeholders can use these data as a resource for implementing new circular building design strategies towards mitigating housing-related greenhouse gas emissions.

Source: Keena and Friedman 2022.

future use patterns) (Barbosa, Woetzel and Mischke 2017). Big data on carbon, energy and material flows can be harnessed to provide stakeholders with an at-a-glance interactive look at the causes and effects of material choices and decisions (Keena 2017; Keena and Dyson 2017; Keena and Dyson 2020). Figure 6.2 shows an example of a dashboard that allows stakeholders to view multiple windows to track, communicate, and assess material flows and environmental impacts across the life cycle. Importantly, it harnesses artificial intelligence and big data to enable users to question the provenance and reliability of the data and to compare different sources.

Future intelligent data frameworks such as this will increase the transparency and reliability of assessment tools as they become more interoperable and accessible to air quality sensors and software that help track the emissions of material processes at different phases of the life cycle, from extraction to demolition. They will also allow for better real-time monitoring of the labour and environmental conditions of construction sites. In Canada, the new Data Homebase application enables stakeholders to access the estimated energy use, carbon emissions and affordability indexes of residential buildings across cities (see **Box 6.1**).

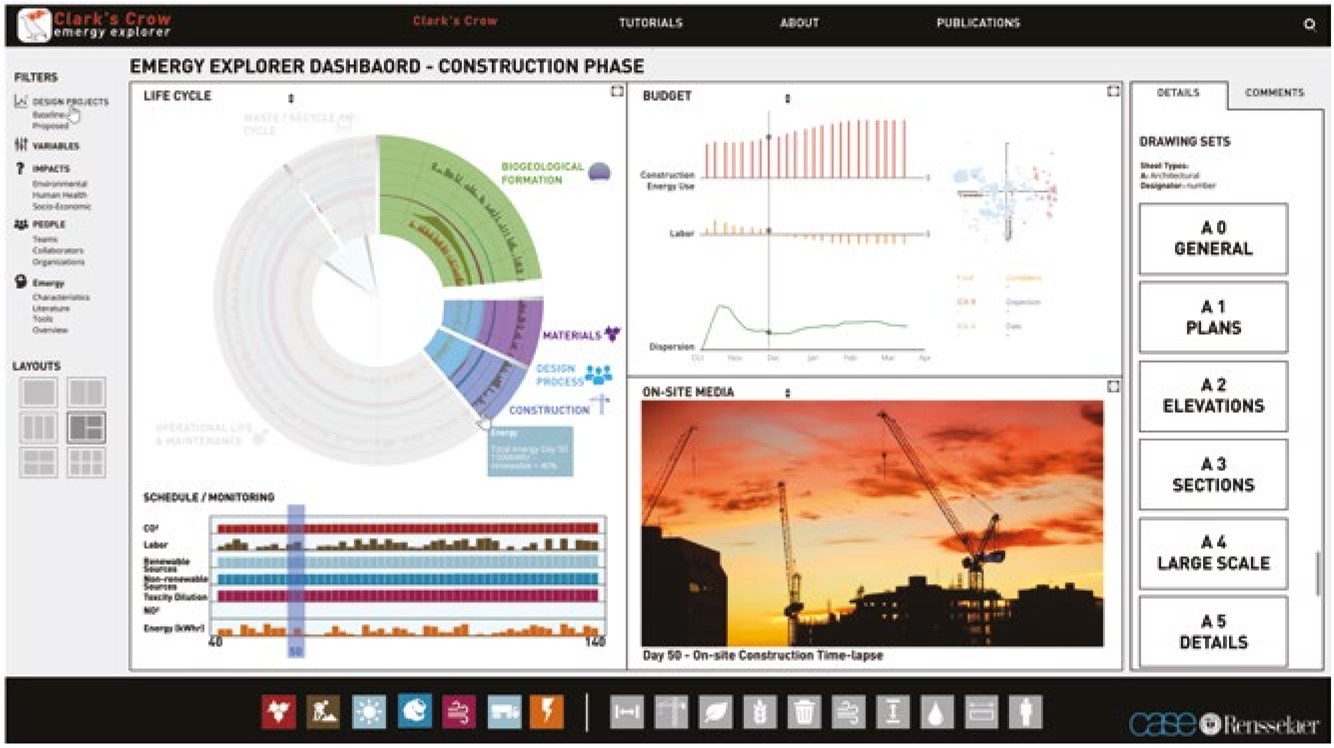
Visualisation frameworks that trace a material's lineage and characteristics, as well as predict its future impacts on operational energy and end-of-life, are especially critical for the design architects and engineers who have an outsized impact on the decision-making process and typically have very little time to justify material specifications. This is crucial to ensure confidence in the shift towards locally sourced circular, bio-based, and earth-based materials, since species quality and structural characteristics vary extensively. Huge strides have been made in developing accessible design standards for bamboo (Harries et al. 2022), but frameworks for other species are lacking, with guidelines almost non-existent for forest detritus and agricultural by-products.

Assessment Tools Need to Consider the Full Ecosystemic Impacts of Bio-based Materials

It is critical that future tools assess the local impacts on regional ecosystems for different practices of extracting materials.

In scaling up the global shift towards bio-based materials, it is critical that future tools assess the local impacts on regional ecosystems for different practices of extracting materials, especially primary timber and bamboo. Life-cycle assessments for bio-based construction materials have rarely considered the impacts of land use and land-use changes (Hoxha et al. 2020). Besides carbon and climate change, land use for biomass supply also impacts biodiversity and ecosystem services (Verkerk et al. 2014; Gaudreault et al.

6.2 The Clark's Crow "at a glance" data tool



The tool shows the environmental and socio-economic impacts of material choices across the entire life cycle.

Source: Keena, Aly Etman and Dyson 2020.

2016; Ferrarini et al. 2017). Given the huge regional variations of ecosystems, suitable biomass sources and production scales need to be assessed and identified at the regional level to ensure that the use of biomass supports healthy ecosystems.

Current life-cycle assessment methods can support holistic assessment of some environmental impacts but not all. For example, assessing the impacts on biodiversity and ecosystem services will need other complementary tools and data for regional assessment (Winter et al. 2017; VanderWilde and Newell 2021). Different life-cycle assessment methods (for example, attributional and consequential life-cycle assessments) and carbon accounting frameworks exist. The suitability and practicality of these methods to support policymaking for bio-based building materials will need to be assessed.

At the global scale, there is an urgent need to support the development of predictive models to anticipate the impacts on global ecosystems of scaling up bio-based material processes. The use of biomass affects diverse ecosystems that remove CO_2 from the atmosphere, which should be considered when assessing the impacts of bio-based materials. For example, one study linked a life-cycle assessment model of cross-laminated timber with a forest dynamic simulation for a pine forest in the southeastern United States to understand the carbon fluxes associated with the life cycle of both cross-laminated timber and forest lands supplying wood across 100 years (Lan et al. 2020).

Further predictive models and assessment studies are urgently needed for all regions, especially in emerging economies, to set the policy for sustainable management of both forest-based and agricultural-based biomaterial stocks.

6.4 Tools for Greenhouse Gas Assessment Are Needed for District-Scale Planning

Urban planning often ignores emissions related to site preparation, which can account for 12% of a neighbourhood's life-cycle emissions.

Greenhouse gas assessments at the level of individual buildings are an important step and are becoming common in many parts of the world. However, broader perspectives are also needed. Urban planning often completely ignores emissions related to the preparation of the building site (e.g., earth moving and soil stabilisation), infrastructure construction and maintenance, traffic, and soil and vegetation carbon sinks. Such omissions can lead to skewed perspectives on priorities in low-carbon urban development.

BOX 6.2

FINLAND'S "AT-A-GLANCE" AVA TOOL FOR GREENHOUSE GAS ASSESSMENT AT THE NEIGHBOURHOOD LEVEL

Helsinki, Finland is using a neighbourhood-level greenhouse gas assessment tool called AVA, which can be applied to detailed plans covering one to five buildings, or urban blocks of apartments and/or office buildings. AVA was developed to be applied quickly and practically to typical urban plans, so that a planner can use it without expert understanding of greenhouse gas assessments. Despite the tool's simplicity, its results have been shown to generally align with other methods (Tevajärvi 2022).

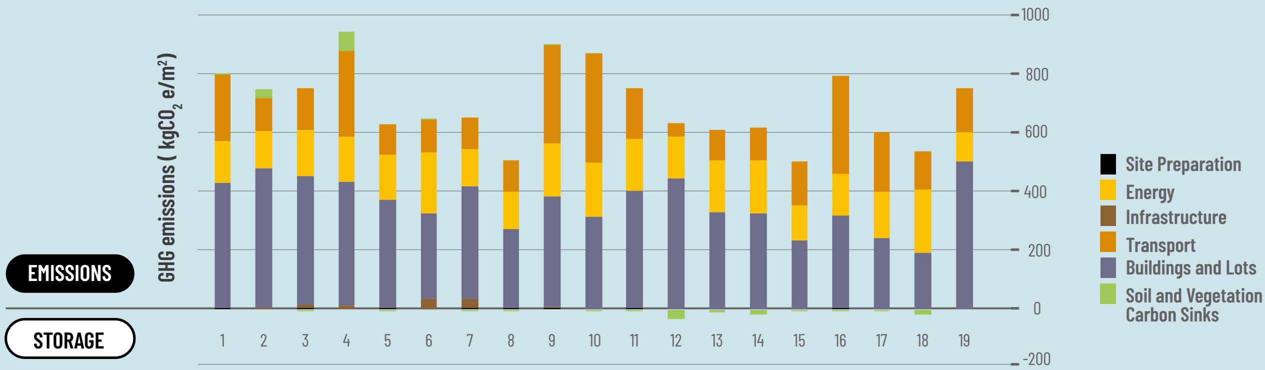
Key goals in AVA's development were to capture the main sources of emissions in buildings and infrastructure and to focus on issues that urban planners can influence, such as ideal material requirements for structures and foundations, the choice of concrete or timber for the structural frame, the level of energy efficiency, and a cap on the overall carbon footprint. This foreshadows an upcoming law that will make carbon footprint calculations required for all new buildings (Kuittinen, Ilomäki and Koskela 2021).

The speed and ease of use of AVA allow designers to compare the environmental impacts of different options for a site. Importantly, the tool can be applied to larger and more complex plans, although users need to be aware of the tool's limitations as a ballpark assessment tool; on more complex infrastructure needs, assessments will need to be supplemented by more expert analysis.

Figure 6.2 shows results from AVA assessment of 19 different detailed plans in Helsinki, reflecting a diversity of built area sizes and building uses. In line with previous Finnish studies (Puurunen *et al.* 2021), the results indicate that three main activities dominate emissions: building construction, energy use and transport. In most cases, the construction and maintenance of buildings is by far the largest category of emissions. This shows a clear shift from older studies, which tend to show the dominance of operational energy in emissions. The contribution of buildings and construction to emissions is likely to grow, as scenarios indicate that both energy production and transport can be decarbonised relatively swiftly based on Helsinki's targets and current actions.

The results in **Figure 6.3** are revealing. For example, the impact of a timber frame is shown in case 18, which has the lowest emissions from building construction. Case 4 is located in a wooded area, which leads to a noticeable impact resulting from the loss of carbon sinks. In contrast, cases 12, 14 and 18 show developments where soil and vegetation carbon sinks were strengthened during the assessment period.

6.3 Greenhouse gas emissions per total floor area for 19 detailed plans assessed in Helsinki (50-year assessment period)



The construction and maintenance of buildings is by far the largest category of emissions.

Note: The assessed developments represent a wide variety of building uses and total floor area. Source: Puurunen 2023.

The importance of accounting for these wider-area emissions is heightened by the insight that these are the very first emissions released during the life cycle of an urban project. For example, studies in Finland have shown that emissions from site preparation can account for up to 12 per cent of a neighbourhood's total life-cycle emissions (Puurunen et al. 2021). In part to address this challenge, the city of Helsinki has adopted the newly developed AVA tool to assess emissions at a neighbourhood scale (see **Box 6.2**)

Climate pledges and decarbonisation pathways that ignore scope 3 emissions must be seen as inadequate.

Increasingly, cities are adopting municipal greenhouse gas assessments to account for local-level emissions. Under the Global Covenant of Mayors for Climate and Energy, more than 12,000 member cities estimate their annual emissions based on the Global Protocol for Community-Scale Greenhouse Gas Inventories (Global Covenant of Mayors 2016). Typically, city-level pathways to decarbonisation are based only on scope 1 emissions (emissions produced within the city limits) and scope 2 emissions (energy-related emissions) (Fong et al. 2021), with assessments for buildings based on the standard EN 15643. Scope 3 emissions, which include emissions that occur outside the city boundary as a result of activities taking place within the city, have received less attention (Linton, Clarke and Tozer 2022). These include the embodied emissions of building materials and other products used in cities but produced elsewhere.

Climate pledges and decarbonisation pathways that ignore scope 3 emissions must be seen as inadequate. Consumption-based accounting of emissions is an absolute necessity as one basis for solving the climate crisis. For example, a recent comparison of greenhouse gas assessments in 10 European cities found that, in all cities, assessments of scope 1 and 2 emissions revealed significant reductions in emissions (up to 68 per cent) (Harris et al. 2020). However, assessments of scope 3 emissions showed that, in 8 of the 10 cities, consumption-based emissions were rising, by as much as 35 per cent. This highlights the important role of measuring and tackling embodied emissions.

6.5 Global Standards and Labels for Emission Transparency Can Galvanize the Market

If all G7 economies implemented policies that favour low-carbon materials and products, global emissions could be reduced 5.5%.

It is essential that all of the different methods for identifying and declaring materials-related greenhouse gas emissions be brought into globally regulated compliance through transparent labelling. This would help create a level playing field across the supply chain and life cycle. Material producers – particularly in emerging economies where resources for certification are limited – must be supported to enable fair, third-party verification of processes and equipment. For purchasers of materials, such independent verification is needed by supplier, assembly, installation, geography and asset.

The most impactful way to facilitate multi-stakeholder cooperation across global material supply chains is to "close the carbon loophole." This means that developed economies that are now net importers of raw materials – and that have contributed the vast majority of past greenhouse gas emissions – should not be permitted to purchase those materials at "discounted" prices from emerging economies, which are obligated to maintain low prices through lax environmental and labour regulations. Global cooperation is needed to create a new trade paradigm. If all G7 economies implemented policies that favoured low-carbon materials and products, while ensuring fair trade and labour, global emissions could be reduced by 5.5 per cent (1.8 gigatons of CO_2) (IEA 2021).

This would also create a far more equitable system for tracking emissions across the material life cycle. Closing the carbon loophole would provide pathways for producers in the developing world to gain access to new markets, by shifting emissions off the balance sheets of developing economies and placing more accountability on consumers in high-income countries that boast strict environmental regulations at home. Furthermore, a level playing field is essential for the creation of transparent and verifiable international labelling and certification protocols. Public education and policy are critical to ensure that consumers have a better understanding of the social and environmental costs of cheap materials, from forced labour to the degradation of ecosystems, species loss, forest fires, water and air poisoning, etc.

The demand for low-carbon materials can be bolstered by market-based mechanisms, financing, certifications and regulations to lower risks and create a fair, competitive playing field. Border carbon adjustments, such as the European Union-led Carbon Border Adjustment Mechanism, or trade agreements like the U.S. proposal for a Global Arrangement on Steel and Aluminium, both announced in December 2022, are examples of policy instruments that intend to minimise the risk of unfair competition and "carbon leakage" in cross-border carbon accounting.

However, if these mechanisms are to truly support global decarbonisation, then their design must account for the realities of production and demand in emerging economies. Global agreements on carbon-adjusted building material markets and financing should build capacities for transparently identifying and verifying carbon competitiveness, so that materials can be fairly certified (Brenton 2021).

Table 6.2

EMERGING MECHANISMS TO SUPPORT WHOLE LIFE-CYCLE DECARBONISATION OF BUILDING MATERIALS

Performance-based building codes

The emergence of low-cost tracking has enabled greater access to demand-side metrics on energy and water use in buildings. Transitioning to performance-based building codes that draw on these metrics could transform well-established codes. It would also lend a critical opportunity for emerging economies lacking existing building energy codes to leverage their ongoing building boom to leapfrog over outdated prescriptive building codes, which were largely based on "best practice" examples, with "one-size-fits-all" guidelines that are ill suited due to the variability of local micro-climates and building traditions. Performance-based building codes have a greater chance to connect to a range of stakeholders, from global architecture, engineering and construction companies, to owner-builders in informal settings.

Examples: EnergyPlus, Zero Tool, Building Energy Modelling, Autodesk Energy Analysis, Sefaira Building Performance Software, PV Calculator, DSIRE Efficiency/Energy Incentives Database, WUFI.

Carbon footprint assessments

Emerging carbon footprint assessments convey more transparently the potential whole life-cycle impacts of embodied and operational carbon, both for traditional construction materials and for prefabricated systems and assemblies. Through critical comparisons, stakeholders can consider and track the beneficial impacts across the life cycle of computer-enhanced design, procurement and production methods. These benefits can include increasing the efficiency of materials and structures, reductions in on-site emissions from construction, and the improved ability within factories to design for disassembly and circular reuse/recycling. However, anticipating the impact of materials on operational performance is complex and needs to account for factors such as local bioclimate, building typologies, systems integration, and human behaviour and occupation patterns. All of these can cause great variability in the operating performance of a building material and its system.

Examples: EC3 Carbon Calculator, Tally, WoodWorks Carbon Calculator, Athena Impact Estimator for Buildings, Open LCA, GLAD

Embodied carbon labelling

Wide discrepancies currently exist in the methods and quality of the labelling of embodied carbon in building materials. Support is growing for the establishment of an international standards committee to oversee fairness in this labelling. However, more development is needed of methods that address the "carbon loophole," so that the consumers and specifiers of materials in countries with strict pollution controls can share accountability with producers from regions with lax controls. Unfortunately, the inability of many producers (particularly small ones) to pay for the certification of their products can lead to them being further disadvantaged by carbon border taxes – thus leading to the further loosening of local regulations to ensure that exports remain competitively priced.

Examples: EC3 Carbon Calculator, Cradle to Cradle certified, Declare Living Future Institute.

Low-carbon public procurement practices

Municipal and national governments are setting policies and aggressive targets that limit their choices to low-carbon alternatives when selecting contractors. This is resulting in the establishment of leading industry precedents for integrated decarbonisation across multiple scales of infrastructure and buildings.

Example: See **Box 6.2** on Helsinki, Finland

Industry pledges

Global leaders in the architecture, engineering and construction industry are developing pledges, internal benchmarks and novel methods to track the carbon impacts of their activities. Despite rampant accusations of greenwashing, with many risks of data manipulation (especially when self-reported), rating agencies and efforts such as the Science Based Targets initiative work with businesses to agree to a science-based target that limits a business' global share of greenhouse gas emissions, with independent verification. However, firm commitments need to be secured. The climate pledges made at the 2021 United Nations Climate Conference in Glasgow were followed by lawsuits for greenwashing in advertising; thus, many firms are choosing to avoid scrutiny.

Examples: Green Building Principles: The Action Plan for Net-Zero Carbon Buildings, Sustainable Construction Leaders Peer Network, Contractor's Commitment to Sustainable Building Practices

Models for coordination

Models for coordination across the forestry, agriculture and construction industries are emerging for enhanced cooperation on land use and the supply of bio-based building materials. The aim is to develop supply chains and products derived from the upcycling of forest detritus and agricultural waste by-products into building materials, which would in turn greatly reduce carbon emissions from forest fires and crop burning.

Example: Build Carbon Neutral Calculator

Carbon offsets

As governments, industry players and others strive to meet net zero emission deadlines, demand is growing for carbon offsets and renewable energy credits. This is setting the stage for an escalating carbon offset economy. However, the actual decarbonisation of building material production processes may be hampered by the ability of industries to market so-called net zero products through the use of carbon offsets of varying quality. Greater regulation is needed in certifying decarbonisation of the actual processes of material production.

Example: See **Box 6.3** on Lendlease Americas

BOX 6.3

NET ZERO CONSTRUCTION AT LENDLEASE AMERICAS

The global construction company Lendlease Americas was able to reach net zero emissions for its roughly $2 billion construction operations during 2021 and 2022. The company used life-cycle analysis to inform multiple concurrent decarbonisation pathways. To maintain alignment with a pathway to keep global temperature rise below 1.5 degrees Celsius, Lendlease has committed to achieving carbon neutrality in its scope 1 and scope 2 emissions by 2025, and absolute zero carbon emissions across scopes 1, 2 and 3 by 2040. The company achieved its 2025 goals early for its U.S. construction business, largely by reducing its significant operational emissions.

During financial years 2020 and 2021, Lendlease's U.S. operations released a total of 15,799 metric tons of CO_2-equivalent emissions. Of this, scope 1 emissions totalled 9,411 tons, derived from the use of fuels for temporary construction electrical power generation and fuels used in operating major plant and equipment such as excavators and tower cranes. Lendlease used natural gas and other fossil fuels to provide heating during concrete placement in colder winter months. In addition, the company emitted indirect scope 2 emissions totalling 6,390 tons through the use of electricity for site lighting and other temporary uses.

Lendlease is implementing the following strategies to reduce both scope 1 and scope 2 emissions:

- utilizing electric plant and equipment through expediting permanent power utility connection
- use of biofuels and renewable diesel
- leveraging battery storage solutions to reduce generator sizing
- Elliminating fossil fuel heating of concrete placement operations during winter months
- leveraging on-site renewables such as solar for small-scale applications
- purchasing carbon offsets and renewable energy credits.

Lendlease chose several U.S. renewable energy projects to procure carbon offsets for its scope 1 emissions, and also purchased high-quality renewable energy credits for its scope 2 electricity use. Through these measures, Lendlease Americas Construction has been operating "net zero" since July 2020. Lendlease believes in the importance of sharing best practices for reducing carbon emissions associated with construction and collaborating with peers to rapidly decarbonise this industry.

Source: Lendlease 2022.

Developments in international trade mechanisms may be able to change the game in combating global climate change. However, for emerging economies that have historically contributed very little to climate change, but where the majority of material production and consumption will take place in the coming decades, it is critical to facilitate the development of a consistent and comprehensive accounting system to accurately measure emissions all along the life cycle and value chain, so that these countries have a fair chance to demonstrate their carbon competitiveness (Columbia Center on Sustainable Investment [CCSI], International Institute for Environment and Development [IIED] and International Institute for Sustainable Development [IISD] 2021). To truly create a level playing field towards global decarbonisation, many emerging economies have taken the position that they should receive a large portion of the proceeds from border carbon adjustments, to support them in adopting low-carbon methods and certifications.

Table 6.2 provides an overview of some of the mechanisms, including carbon labelling, that are emerging to support whole life-cycle decarbonisation of building materials in both developing and developed countries. **Box 6.3** provides an example of how one company, Lendlease Americas, used life-cycle analysis to inform multiple concurrent decarbonisation pathways on the path to net zero.

6.6 Challenges and Next Steps

Excellent analytical tools, frameworks and studies are emerging to help identify key levers and practices for decarbonisation in the building sector. However, these must be supported by appropriate policy, access to quality data, and transparent audits conducted by qualified third-party reviewers. In an effort to increase the transparency of materials, the Design for Freedom Toolkit (Grace Farms Foundation 2022) highlights dozens of relevant certifications, labels and standards that include fair labour audits.

Notably, in the informal sector, stakeholders typically have neither the access to data nor the means to conduct such analyses. However, feedback included in utility bills and other mechanisms can continue to add life-cycle information on the impact of materials on operational energy expenditures, including design tips for material retrofits to reduce costs. This information can then be fed into district and even urban models showing comparisons across households and building types.

This report outlines the most advanced methods in decarbonisation analysis and practices in the formal realm, while suggesting potential pathways for cooperation and exchange between informal and formal construction practices.

7

POLICY Recommendations for Decarbonising Materials in the Global Building Sector

Decarbonizing buildings will not be possible without taking a whole lifecycle approach to their construction and ensuring the rapid decarbonisation of building materials.

DECARBONISING BUILDINGS WILL NOT BE POSSIBLE WITHOUT TAKING A WHOLE LIFECYCLE APPROACH TO THEIR CONSTRUCTION AND ENSURING THE RAPID DECARBONISATION OF BUILDING MATERIALS.

Building material choices made in infrastructure policy, urban planning and building design requirements have profound impacts on GHG emissions. The precise set of policies to optimise building material decarbonisation must be informed by the assessment of the specific context. Regulation is required across all phases of the building life cycle, from extraction of materials through end-of-use of buildings, to ensure the development of a viable, circular supply chain of sustainable material options. Efforts to decarbonise the material supply chain are synergistic with measures undertaken to ensure fair labour and gender equity. This requires radical collaboration and simultaneously supporting material producers/manufacturers and consumers such as architects, developers, communities and building occupants.

Policy makers will need to engage all actors across the entire value chain and concurrently enable the implementation of the three main decarbonisation principles discussed in this report:

- **AVOID** material overuse and new material extraction by building (with) less, actively seeking ways of reusing and recycling buildings and materials.
- **SHIFT** to sustainably produced low carbon renewable building materials such as earth and biobased materials whenever possible.
- **IMPROVE** methods to decarbonise carbon-intensive conventional materials such as concrete, steel and aluminium, and only use them when necessary.

Across regions, implementation methods will vary as patterns in material flow scenarios differ. In highly developed regions, incentives need to focus on the renovation of existing and ageing building stock, whereas in developing regions with rapid rural to urban migration, there is an opportunity to radically re-invent new construction techniques and leapfrog over prior modern practices by dramatically improving conventional material production, reconnecting with existing, local climate-specific building knowledge and vernacular traditions, and shifting to sustainably sourced biomaterials wherever possible.

Annex 3 provides short summaries on how countries that have very different built environment contexts – Canada, Finland, Ghana, Guatemala, India, Peru and Senegal – can pursue decarbonisation using the "Avoid-Shift-Improve" strategies.

To drive market transformation and stakeholder action, governments should take action to:

1. Set the vision, lead by example and improve multi-level governance
2. Make carbon visible through improved data access and quality
3. Adapt norms and standards to allow for the use of circular, alternative or lower-carbon, bio-based building materials and construction practices
4. Accelerate the industry transition
5. Ensure a just transition
6. Strengthen international action and collaboration for collective impacts

7.1 Set the Vision, Lead by Example and Improve Multilevel Governance

7.1.1 Rallying All Stakeholders Behind the Whole Life Cycle Approach

Since it is critical for actors in the buildings and construction sector to work towards the implementation of a whole lifecycle approach to buildings and construction, policy makers should start by taking stock of the current situation and practices in order to bring diverse stakeholders of the buildings and construction value chain behind a common vision to overcome the fragmentation in the sector, and ramp up both the level of action and ambition towards decarbonizing buildings along their lifecycle and make them durable and climate resilient. Box 7.1 highlights GlobalABC Global and Regional Roadmaps as an example product of stakeholder engagement.

BOX 7.1

GLOBALABC ROADMAPS FOR BUILDINGS AND CONSTRUCTION

The GlobalABC Global and Regional Roadmaps for Buildings and Construction in Africa, Asia and Latin America help set pathways to decarbonisation of the buildings and construction sector by 2050. These roadmaps are being cascaded to sub-regional, national and sub-national levels leaping forward towards implementation in over 30 countries/jurisdictions.

The roadmaps are developed through participative stakeholder engagement process and present a comprehensive approach to emission reductions from the built environment along the full life cycle, with aspirational short and medium term and longer-term targets goals. See Roadmaps for Buildings and Construction | GlobalABC

KEY ACTION

INSTITUTIONALISE STAKEHOLDER COORDINATION AND DEVELOP NATIONAL AND SUB-NATIONAL ROADMAPS AND ACTION PLANS FOR THE DECARBONISATION OF THE BUILT ENVIRONMENT

- **Initiate a country-led stakeholder engagement process that helps to bring all actors of the value chain together to identify actions and priorities to transform the buildings and construction sector (e.g. following the model of GlobalABC's Roadmaps for Buildings and Construction).**
- **Establish and institutionalise a coordination mechanism to facilitate collaboration and synergies between actors, facilitate collaborative actions/synergies and ensure these are not affected by short-term political cycles.**

7.1.2 Harness Public Procurement to Support Decarbonisation of Materials

The public sector can play a leading role in enabling building material decarbonisation through its procurement powers. Public procurement expenditures – government purchases of materials, products and services – comprise up to 13 per cent of gross domestic product in member countries of the Organisation for Economic Co-operation and Development, with even higher shares in developing economies (Baron 2016). The impact of public procurement in generating more sustainable growth is outlined in Sustainable Development Goal 12 (Target 12.7).

Policy goals for decarbonisation must be formally linked to the purchasing of materials, with additional budgets in the planning phases for rigorous whole life-cycle assessments for public projects, in order to improve the data on the impact of material choices and serve as examples for effective solutions across specific local climate types. In regions where the vast majority of builders have neither the means nor the inclination to conduct such analyses, public works projects serve as especially critical examples for demonstrating the principles of "Avoid, Shift and Improve" as outlined in this report.

Practical strategies include tenders with life-cycle costing in value-for-money assessments, which include the cost of externalities such as CO_2. Market dialogues and international collaboration can support both material procurers and producers across the supply chain in formulating innovative tenders, and encourage new business models that provide services to support reductions in material use and environmental impacts (Baron 2016).

KEY ACTION

LINK PUBLIC PROCUREMENT WITH DECARBONISATION PRACTICES

- **Formally link policy goals for decarbonisation to the purchasing of materials.**
- **Provide for additional budgets in the planning phases for rigorous life-cycle assessments for public projects and publish the results to improve the quality and quantity of data on the impact of material choices and to demonstrate solutions across climate types and building traditions.**
- **Issue tenders that include life-cycle costing in value-for-money assessments, which include the cost of externalities such as CO_2.**
- **Convene market dialogues and international collaboration to support both material procurers and producers across the supply chain in formulating innovative tenders.**
- **Encourage new business models that support reductions in material use and environmental impacts.**

7.1.3 Empower Cities and Municipalities as Drivers of Change

Governments must improve multilevel governance frameworks and mechanisms to better implement and enforce buildings and construction regulations which support whole lifecycle approaches and low carbon material efficiency strategies.

Cities must be empowered to implement and enforce decarbonisation policies in collaboration with national and sub-national government institutions as part of their local action plans for buildings and construction. They need to promote sustainable energy solutions and encourage passive design, circularity, nature-based and neighbourhood level solutions, incentivizing buildings and construction industry stakeholders as change agents. As champions for implementing and enforcing climate policies and targets, cities are uniquely placed to catalyse this transition through their jurisdiction over land use, authority over housing programmes, role in implementing national policies and building codes, and their role in coordinating with local utilities and stakeholders.

The public sector is often in the best position to implement decarbonisation plans at local or district scale. It can have maximum impact for new development, since strategies for individual buildings can be integrated in synergy with the design of sustainable, electrified grids for the management of energy, water, waste and transport. Policies and ambitious targets from local and national governments establish leading precedents for integrated decarbonisation across multiple scales of infrastructure and buildings (see Box 6.2 on Helsinki). This is only possible if material choices and urban planning avoid driving up cooling demands through the creation of urban heat islands and instead lowers the overall operational carbon of cities by mandating biomass materials and other cool surfaces.

KEY ACTION

IMPLEMENT COORDINATED DECARBONISATION ACTIONS AT THE LOCAL OR DISTRICT SCALE

> Implement local or neighbourhood-level building decarbonisation plans for coordinated action by establishing grid integration schemes and local material banks for and renovating building envelopes or new constructions with low carbon circular or biobased materials.

> Create incentives at the local level to overcome initial and ongoing maintenance costs.

KEY ACTION

MANDATE THE USE OF LIVING SYSTEMS AND BIOMASS TO PROTECT URBAN CLIMATES

> Include minimum requirements in building codes for vegetated surfaces for urban-scale buildings.

> Provide incentives for smaller buildings to incorporate locally appropriate plant species into roofs and façades.

7.2 Make Carbon Visible Through Improved Data Access and Quality

7.2.1 Environmental Labelling Standards and Certifications

There is a need for international environmental labelling standards with established standard protocols and licensed third-party verification for building materials as well as buildings. To ensure the validity of the claims and to facilitate fair competition among producers, transparent, scientifically sound methods and documentation are required. Currently, the International Organisation for Standardisation (ISO) specifies the protocols for all self-declared environmental claims of materials, including what statements, terms and/or graphics are permitted, and provides qualifications and verification methodology. However, regulation and enforcement to ensure compliance is still severely lacking in most sectors, leading to potentially negative market effects.

Rising public interest in environmentally sound construction practices has led to a flood of self-declared environmental claims from material producers, with limited traceability – generating scepticism and backlash. For certification to facilitate a transition to low-carbon materials in a fair and equitable manner, more development is required for methods that address another "carbon loophole," so that the consumers and specifiers of materials in countries with strict pollution controls share the onus for the decarbonisation of the materials they consume with producers from regions with no or minimal controls.

KEY ACTION

PROMOTE CLEAR AND CONSISTENT STANDARDS FOR CARBON LABELLING

> At the very least, all material products should be certified with international standards such as the GHG Protocol Product Standard, ISO14067 or PAS2050. However, there are still so many barriers to getting these standard certifications, and far more support needs to be given to smaller enterprises, particularly in developing regions if there is to be a realistic expectation of fairness across suppliers.

> Support for enforcing fair regulation is absolutely critical, if labels are to be taken seriously in many markets that currently eschew the cost of certification.

> Need to address the backlash from rampant perceptions of 'greenwashing' in the marketplace.

7.2.2 Lifecycle Analysis of Building Materialsin Construction and Renovation Projects

Common metrics and consistent assessment processes allow decision-makers to accurately weigh the trade-offs in prioritising the different decarbonisation pathways, in order to accurately inform efforts to set standards and trade policy. Often just making this data visible (e.g. through labels) can have effects on which pathways are chosen and pursued. However, further development, international cooperation and coordination is urgently required in order to ensure fairness with accurate and transparent data. Many tools are on the market that allow a calculation of the carbon footprint of building materials which is a great first step, however the accuracy and relevance of the data needs substantial development in regulatory and verification procedures. The data availability, especially in developing country contexts needs to be vastly improved. Nevertheless, there are now many tools, such as the EDGE tool, that allow for an assessment of alternatives already, and these methods need to be encouraged in order to spur further development.

Going forward, more sophisticated tools can be further developed to capture the beneficial impacts of computer-aided production methods – from efficiencies in materials and structures to reductions in on-site emissions – and the improved ability of computer-aided, factory-based production to reduce material waste and support design for disassembly and circular re-use. This could also include the value and requirements of non-human living systems. Thus, the values in whole life-cycle assessments need to expand to include the work of the geo-biosphere, because in some cases it has taken millions or even billions of years for the Earth to form certain raw materials – such as the iron ore required to make steel – that are therefore irreplaceable, but even seemingly abundant bio- or earth-based materials have highly variable impacts depending on their origin (Keena and Dyson 2017).

KEY ACTION

PROMOTE EVIDENCE-BASED MATERIAL SELECTION

> **Mandate the assessment of the carbon impact of building materials (LCA) in construction and renovation projects.**

KEY ACTION

INCREASE THE AVAILABILITY OF HIGH-QUALITY AND IMPROVED METHODOLOGICAL DEVELOPMENT

> **Fund research to determine best practices for life-cycle analysis of ecosystem impacts, as well as research and methodological development for whole life-cycle assessments that include the geo-biosphere.**

7.2.3 Improve Access to Data

Knowledge about the embodied carbon content of the current building stock is needed for calculating emission baselines and setting mitigation targets, and for monitoring, reporting and verification (MRV).

KEY ACTION

IMPROVE ACCESS TO TRACEABLE, TRANSPARENT, RELIABLE AND VERIFIABLE DATA

> **Purchase, provide or subsidise data needed for assessments for key stakeholders such as developers in contexts where these data are cost-prohibitive.**

> **Dramatically increase the support for ongoing tool development and use for stakeholders across the supply chain to be able to make rapid design and procurement decisions and be able to verify the provenance of materials in real time.**

> **Encourage digitalisation and the development of building passports to assist in standardising data and making them traceable, transparent, and verifiable.**

> **Fund research to further develop data banks that can support fair certification and labelling of materials and buildings.**

7.3 Adapt Norms and Standards to Allow for The Use of Alternative or Lower-Carbon Building Materials and Construction Practices

7.3.1 Introduce/Strengthen Building Codes to Address Embodied Carbon

Much attention has been focused on reducing the carbon impacts of building materials in the context of formal, regulated practices. However, most global building sectors have a high share of informal construction, with more than 60 per cent of countries lacking mandatory building energy codes; as such, more than 5 billion square metres have been built without regulated performance requirements (UNEP 2022).

Introducing and mandating performance-based building codes that address the performance of the building envelope and climate impact of building materials is essential. If enforced, building energy codes can be the most effective policy instrument for influencing energy use in both new construction and retrofits (IEA 2018b). Emerging economies that lack existing codes have an opportunity to avoid the restrictions of prescriptive building codes from the first wave of "environmental" building standards, which were largely based on "best practices" and were not always adaptable to local conditions and practices.

KEY ACTION

ADOPT PERFORMANCE-BASED BUILDING CODES

- **Adopt (or strengthen) building codes that encourage or mandate evidence-based and material performance-based requirements in design.**

7.3.2 Enforce Performance-Based Building Codes

With the growing adoption of low-cost digitised tracking methods, as well as access to demand-side metrics such as energy and water use, performance-based building codes have a greater chance to connect to a range of stakeholders across sectors, from global architecture, engineering and construction companies to occupant/builders in informal settings. However, several key impediments need to be addressed for widespread inclusion of embodied carbon in building codes.

KEY ACTION

ENFORCE PERFORMANCE-BASED BUILDING CODES THAT INCLUDE THE ENVIRONMENTAL PERFORMANCE OF MATERIALS

- **Mandate the transition from non-renewable materials to low-carbon bio-based renewables, hybrid, and recycled materials, wherever possible.**
- **Build systems to collect data on operational energy costs and to create interactive platforms for users to track the energy costs of different material decisions.**

7.4 Accelerate the Industry Transition

7.4.1 Rapidly Decarbonise Conventional Non-Renewable Materials

Cement, steel and aluminium are the three largest sources of embodied carbon in the building sector. One of the lowest hanging fruits is to facilitate and/or mandate the adoption by industry as well as energy infrastructure planners of already developed best available technologies for decarbonisation and to maximise the use of clean energy in manufacturing processes.

Adopting decarbonisation technology in a manner that reduces emissions globally will require close coordination of national and international efforts in data collection, standards, and leadership in trade mechanism development (see chapter 6).

KEY ACTION

ACCELERATE INDUSTRIAL ELECTRIFICATION ACROSS THE BUILDING LIFECYCLE, FROM MATERIAL PRODUCERS TO CONSTRUCTORS, OWNERS AND DEMOLITION

- **Leverage advancements in low-carbon electricity, both from the grid and on-site (or district) renewable power generation sources.**
- **Invest in the development of neighbourhood micro-grids and peer-to-peer power sharing between different stakeholders.**

KEY ACTION

ACCELERATE MULTIPLE PATHWAYS TO DECARBONISATION IN THE CEMENT SECTOR

- **Increase funding and provide incentives for public-private partnerships to accelerate the development, demonstration and commercialisation of concrete decarbonisation technologies and techniques.**
- **Invest in materials science capacity in concrete technology and practice.**
- **Invest in the transition to biobased cementitious binding materials from agricultural and forest detritus.**
- **Promote the research and development of Carbon Capture, Utilisation and Storage (CCUS) technology that could reduce carbon emissions and increase material strength, thereby reducing use.**
- **Improve building codes to mandate the design and implementation of 'circular', modular concrete components that can be easily disassembled and reused.**

KEY ACTION

REDUCE THE CARBON FOOTPRINT OF THE STEELMAKING SECTOR

- **Encourage upgrades of existing plants to best available technology in steelmaking.**
- **Provide financial and structural support for phasing out coal-based primary steelmaking technologies (blast furnace/basic oxygen furnaces) with low-emission technologies (direct reduced iron coupled with electric arc furnaces).**
- **Incentivise material efficiency strategies across the**

steel life cycle to increase steel's circularity and reduce its embodied carbon.

- Fund development and demonstrations of transformational new methods for CCUS, hydrogen steel production and electrolysis of iron ore.

KEY ACTION

INVEST IN LOW-CARBON POWER FOR ALUMINIUM PRODUCTION, AND MINIMISE DOWNCYCLING

- Sharply increase the availability of low-carbon electricity for aluminium production to reduce the high embodied carbon of virgin aluminium.
- Incentivise material efficiency strategies across the aluminium life cycle.
- Improve collection and grade-specific sorting at end-of-life to maximise the use of scrap in future aluminium production without the risk of downcycling to low-value applications.
- Invest in and enable the transition of digitised off-site manufacturing to greatly reduce yield losses in manufacturing.

7.4.2 Promote the Transition to Low-Carbon, Biodiverse Materials

Designing with nature-based processes means shifting from "extracted" non-renewables to "grown" renewables

To decarbonise, the built environment sector must learn to design with nature-based processes. This means shifting from "extracted" non-renewable materials to "grown" renewable materials. The decarbonisation of the cement sector and other major emitters can be enhanced by shifting to bio-based materials and other low-carbon replacements. However, these emerging methods are often not yet cost competitive, and widespread biases remain that protect entrenched methods. Sustainably scaling up implementation cannot be enforced without substantial investment in research and development alongside incentives and/or enforceable building codes. There are substantial dangers of an unregulated shift towards biomaterials backfiring and causing unmitigated environmental degradation.

KEY ACTION

PROMOTE THE ADOPTION OF SUSTAINABLE MANAGEMENT AND PRODUCTION OF BIO-BASED MATERIALS

- Adopt both "push" and "pull" market approaches to scale up sustainable bio-based building materials, by pushing to create consumer demand by supporting low-carbon building material enterprises at the local and bioregional level to develop and market new products, whilst cultivating broad public interest and education through powerful advertising and public education campaigns.
- Create local economic incentive schemes across timber, biomass and renewable building material producers who improve local and regional biodiversity conservation and enhancement practices.
- Accelerate international and local regulatory frameworks to normalise industry adoption of bio-based materials, including by standardising material performance criteria, integrating these materials into building codes and training stakeholders in the mainstream construction industry.

KEY ACTION

FACILITATE THE ADOPTION OF LOCALISED, LOW-CARBON BUILDING MATERIALS

- Facilitate and invest in industrial enterprises promoting the use of localised, low-carbon earth masonry and replace high-carbon cementitious material and binders with secondary and bio-based binders wherever practical.
- Dramatically reduce the risk of regional forest fires and increase the carbon sequestering productivity of regional forests and agricultural lands by facilitating education and investment in enterprises focused on collection, incineration and upcycling of forest, agricultural and biomass resources.
- Promote investment and incentivise the use of by-product resources in the improvement of conventional building materials – such as fly ash from coal and agricultural industries or sewer sludge ash.

KEY ACTION

PROMOTE AWARENESS AND CAPACITY-BUILDING AMONG BUILDING PROFESSIONALS

- Partner with industry associations to educate building design professionals about alternative, low-carbon construction materials and components (both virgin and secondary materials), and about the potential environmental impacts across the life cycle when selecting materials for a building.

7.4.3 Incentivise Circular Economy Approaches for Re-Use and Recycling

Recycled materials are not yet available in sufficient quantities and qualities

Despite growing awareness, most material cycles continue to be more linear than circular. As a result, non-renewable, energy-intensive materials still supply the majority of demand. So far, recycled materials are not available in sufficient quantities and qualities, and the gap between supply and demand for recyclables is growing in most sectors. A new supply-and-demand model is needed, with new enterprises that allow for the careful dismantling of buildings and for the storing, preparation and maintenance of second-cycle materials for resale that will enable circular economies while providing job opportunities.

In developed economies, it is critical to improve industry methods to repurpose the massive quantities of failing concrete and steel from 20th-century infrastructure that are nearing the end of their first life, so that they can be transformed into material "banks" for new construction and slow the pace of non-renewable material extraction. Government incentives, awareness campaigns, and legal and regulatory frameworks have shown to be effective to incentivise approaches for re-use and recycling (Liu, Bangs and Müller 2013). Recycling systems for building materials tend to require similar kinds of support across countries, including promoting markets for re-usable products, providing incentives for the creation of re-use centres (Forrest 2021) and developing specialised contractors.

To facilitate this, far more investment is required for research and development and for equipment to recover and process construction, renovation and demolition waste materials.

KEY ACTION

ADOPT DESIGN POLICIES TO PROMOTE CIRCULARITY, RESOURCE EFFICIENCY, LONG BUILDING LIFESPANS AND ZERO-WASTE RENOVATION

- **Incentivise building designs that last as long as possible and, where possible, incorporate design for disassembly and modular construction to facilitate end-of-life recycling .**
- **Adopt renovation policies that encourage the diversion of end-of-life material for recovery and recycling, promote regulation and measuring of whole building life-cycle carbon emissions, incorporate design for disassembly, and provide quality long-lasting material assemblies in retrofit solutions.**
- **Promote the consideration of end-of-use strategies during material specification in the design of new buildings and renovation solutions to avoid waste and associated emissions later in the building life.**
- **Incentivise a marketplace for material re-use and develop standards to ensure the quality and efficacy for their use, in order to provide assurance to actors in the building sector.**

KEY ACTION

INCREASE RECYCLING RATES FOR KEY BUILDING MATERIALS

- **Target economic incentives to increase overall recycling volumes, incentivise efficient collection and sorting to create competitive secondary markets, and put premiums on the cleanliness of recycling streams to minimise downcycling.**
- **Facilitate stakeholder engagement among designers and recyclers to identify chokepoints and problems with the quality of supply.**
- **Invest in new equipment for collecting, sorting and converting secondary materials onsite at the time of building deconstruction so that it can be efficiently repurposed into a new life cycle with its value retained.**
- **Put in place market incentives (recycled content) and regulatory incentives (collection targets) that ensure that polymers collected from construction, renovation and demolition waste are diverted from landfills and towards recycling.**

7.4.4 Promote Building Re-Use and Renovation Instead of New Build

In developed urban areas, the highest carbon saving strategy is the preservation of existing building stock. Much can be done to promote the reuse of buildings, components and materials by modernising zoning and building regulations, in particular to allow for the transition of under-utilised office and commercial spaces to be converted into housing.

KEY ACTION

DEVELOP COMPREHENSIVE ADAPTIVE REUSE PROGRAMS

- **Remove regulatory barriers to the reuse of buildings and components.**
- **Prioritise and expedite adaptive reuse projects when processing zoning applications.**
- **Support the development and distribution of toolkits for adaptive reuse.**
- **Develop adaptive reuse funding to encourage the repurposing of buildings over demolition and construction.**
- **Develop a comprehensive district-level plan for the future that includes preservation strategies.**

7.5 Ensure a Just Transition

7.5.1 Couple Social and Environmental Justice in Developing Ethical Decarbonisation Policies

A just transition means that the benefits of a green economy are widely shared across all sectors of society, ultimately advancing all of the Sustainable Development Goals (SDGs). Increasing stakeholder engagement and cooperation across the lifecycle, from producers to demolition companies, is critical to ensuring a just transition. However, a coherent climate mitigation strategy must be coupled with assertive regulation of labour markets, and without it a just transition could fail, as multiple building material sectors are already some of the highest-at-risk for forced and unjust labour practices.

The transition to bio-based and circular material economies may exacerbate these risks across the supply chain, especially in informal economies where building codes are extremely difficult to enforce. Therefore, it is crucial that governments seise the opportunity of coupling social and environmental justice with fair and visible labelling and certification processes to raise awareness among consumers, since the two issues combined may ultimately have greater market 'pull' than either issue labelled separately.

KEY ACTION

ENGAGE STAKEHOLDERS ACROSS THE SUPPLY CHAIN BY FUNDING JUST TRANSITION PROGRAMS, LABELLING AND CERTIFICATION

> **Anticipate and fund problem areas for a just transition, particularly in conventional high-carbon material sectors.**
> **Highlight and encourage the resolution of existing inequities.**
> **Promote the widespread use of Just Transition planning Toolkits such as by Climate Investment Funds and Design for Freedom.**
> **Support industry to secure workers and their communities affected by downscaling of conventional processes and encourage synergies with new opportunities and replacement methods that are biobased or circular.**
> **Encourage inclusive and transparent planning.**

7.5.2 Tackle Gender Bias in Both Formal and Informal Building Sectors

Sustainable Development Goal 5 is dedicated to ending gender inequality that creates impediments to effective sustainable development. As outlined in the 2022 report of the United Nations Secretary-General, better environmental outcomes can be attained through achieving gender equality and the empowerment of women and girls in the context of climate change and disaster risk reduction policies. Increased participation of women in decision-making and management of regional natural resources can result in more inclusive and equitable governance as well as more favourable conservation outcomes (United Nations 2022b). There are opportunities to address gender and minority inequalities across the building lifecycle including land use, planning, design, construction, management and end-of-life **(see FIgure 7.1)**.

Although gender bias is prevalent across the built environment sector, it tends to manifest differently across regions. In the formal sectors, the two principal issues to act on are: 1) closing the large gender pay gaps that persist across architecture, engineering and construction industries, (AIA, 2020) and 2) addressing the dominance of men in senior decision-making and administrative roles. In many informal construction sectors, women's economic contribution to settlements remains unpaid, unrecognised and undervalued. Women are often employed in the most hazardous, labour-intensive and low-paying jobs, with gender pay gaps ranging from 30 per cent to 50 per cent (Baruah 2010).

KEY ACTION

CLOSE THE GENDER PAY GAP AND IMPROVE WORKING CONDITIONS

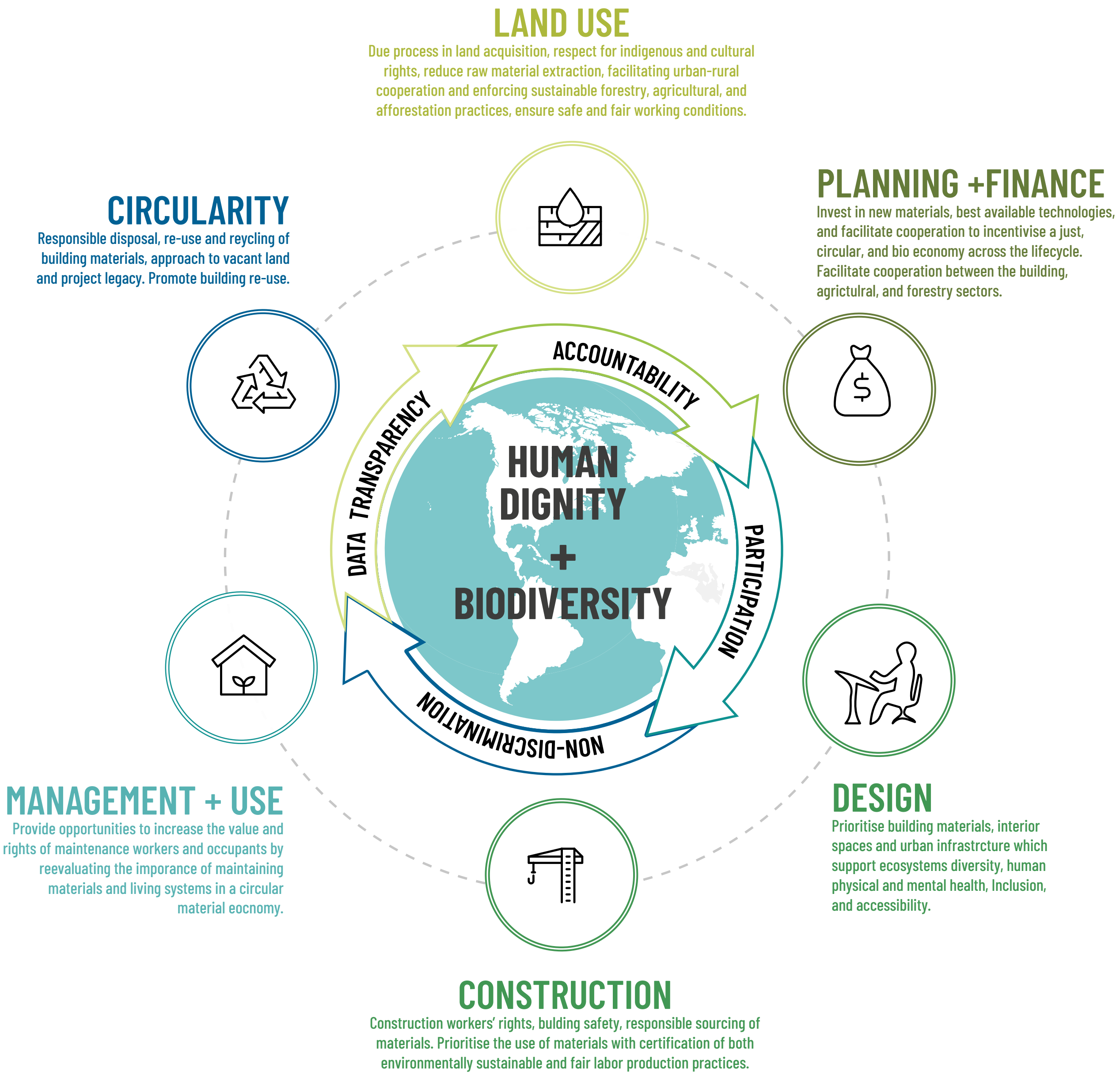
> **Incentivise gender inclusion in government contracts and prioritise project approvals for companies that promote women to leadership positions.**
> **Create investment funds for female career innovation and promote skill development among casual labour.**
> **Enforce national and municipal regulations for safety and improved working conditions at construction sites.**

7.5.3 Improve the Training and Capacity Building Offer for Stakeholders Along the Whole Supply Chain, in Both the Public and Private Sector

The success of government policies, financial incentives, regulations, and schemes in reducing carbon and improving the resilience of the building sector will depend on the availability of a skilled workforce to implement these changes. The shortage of "green-collar" professionals with cutting-edge skills in energy efficiency, low carbon engineering, and skilled construction labour has been identified in a number of countries as a major obstacle in implementing national strategies to cut greenhouse gas emissions or address environmental changes (International Labour Organisation, 2011).

Overall, the challenge of promoting and implementing high performing buildings lies in the transition from traditional construction practices to sustainable alternatives and the lack of skills is considered a bottleneck for the growth of a low carbon building sector.

Figure 7.1 Humans are Part of a Livnig Ecosystem: Framework for dignity across the built environment lifecycle



Source: Partially adapted from Institute for Human Rights and Business (2022).

KEY ACTION

EMBED ENVIRONMENTAL SUSTAINABILITY, RESOURCE EFFICIENCY AND CLIMATE RESILIENCE WITHIN ALL MAINSTREAM LEARNING, INCLUDING NATIONAL CURRICULA, APPRENTICESHIPS, DEGREES AND PROFESSIONAL QUALIFICATIONS

- Promote awareness among building design professionals of alternative low-carbon construction materials and components (both virgin and recycled materials).
- Include training as an integral component of national building and construction sector strategy, involving industry and social partners in the design and delivery of training, combining practical and theoretical knowledge, and targeting initiatives towards migrant and informal workers as well as small construction businesses.
- Enhance knowledge sharing, foster collaborative curriculum development, encourage experiential learning and exchange programs, strengthen partnership and resource sharing, provide more technical assistance and capacity building support, as well as funding and incentives.

7.6 Strengthen International Action and Collaboration for Collective Impact

7.6.1 Address the Decarbonisation of Materials and Embodied Carbon in Ndcs

At the international climate level, action is required for countries to address embodied carbon in their Nationally Determined Contributions (NDCs) towards reducing emissions under the Paris Agreement. Despite the massive contribution to global emissions from embodied carbon within building materials, it has previously been under-addressed in strategies to reduce building emissions. Thus, related actions and targets should be introduced into NDCs.

KEY ACTION

INCLUDE SMART GOALS FOR DECARBONISATION OF THE BUILDINGS AND CONSTRUCTION SECTOR

- **Ensure that commitments in NDC reflect coherent policies presented in this chapter, with a key emphasis on materials industry decarbonisation and decisions made during the design phase, either at the national, subnational, architects, or contractors/implementer levels.**

7.6.2 Development of International Trade Mechanisms to Ensure Decarbonisation of Emerging Economies

International cooperation is required to regulate fair certification and trade across borders and regions. Labelling standards and adequate verification mechanisms need to be fairly supported across economies to reduce the wide discrepancies in methods and quality.

For true decarbonisation of global material flows, it is necessary to close a "carbon loophole" that disadvantages producers from regions with strict pollution controls that must compete unfairly with producers with more lax controls. In turn, it is critical to help smaller producers, especially in emerging economies, achieve certification for their methods. Currently, some of the lowest-carbon practices are being unfairly penalised with cross-border carbon taxes because they cannot afford, or lack access to, certification processes.

Developments in international trade mechanisms may be able to change the game in combating global climate change. For emerging economies that historically have contributed very little to the impacts of climate change, but where the majority of the production and consumption of materials will occur in the coming decades, it is critical to facilitate the development of a consistent and comprehensive accounting system to accurately measure emissions all along the life cycle and value chain. This will enable these countries to have a fair chance to demonstrate their carbon competitiveness in their own domestic building booms, as well as in the production of materials for export (CCSI, IIED and IISD 2021).

For policy mechanisms to create a truly level playing field towards decarbonisation, many emerging economies that so far have not contributed greatly to climate change have taken the position that they should receive a significant portion of the proceeds from cross border carbon adjustment mechanisms, for example, to support them in the adoption of low-carbon production methods and certifications.

KEY ACTION

PROMOTE CLEAR AND CONSISTENT STANDARDS FOR CARBON LABELLING

- **Ensure that regulation and enforcement of domestic carbon labelling matches ISO standards.**
- **Establish an international standards committee for carbon impact labelling of building materials to address discrepancies in methods and quality and create pathways towards enforceable regulation.**
- **Close the "carbon loophole" in carbon offsets by developing a sliding scale of relevance, whereby the process most closely associated with the actual decarbonisation of material processes gets the most credit.**
- **Develop trade mechanisms to support emerging economies.**
- **Ensure a fair playing field for low-carbon building materials through international and multilateral engagement.**

8

CONCLUSION
And Discussion

THE BUILT ENVIRONMENT PROCESS IS COMPLEX. TECHNOLOGY AND BIG DATA HAVE A CRITICAL ROLE IN HELPING TO ESTABLISH COLLABORATIVE NETWORKS, WITH EFFICIENT CONSTRUCTION PRACTICES THAT TRACK MATERIAL, ENERGY AND INFORMATION FLOWS ACROSS BUILDING LIFE CYCLES AND GLOBAL ECOSYSTEMS.

To mitigate dangerous ongoing climate change, it is critical to move aggressively to decarbonise the built environment sector. Across regions, methods will vary in implementing the three main decarbonisation principles outlined in this report: 1) Avoiding non-renewable extraction, 2) Shifting to bio-based sustainable materials, and 3) Improving conventional building materials and processes.

Material flow scenarios for developed versus developing countries highlight key differences. In developed countries, the focus should be on incentivizing the renovation of existing and ageing building stock to transition to high-performance buildings. In developing countries, rapid urbanisation underscores the need to set and then enforce performance-based building energy codes for new construction, starting with the public sector to set the standard. In emerging economies, policies that focus on the decarbonisation of the built environment sector must also address the needs of the informal and semi-formal construction sectors, where the bulk of the labour force resides.

Reducing embodied carbon in building materials to net zero is achievable by 2050, if we promote the use of best available technologies for conventional materials, combined with a major push to advance the upcycling of biomaterials from forest and agriculture streams. The greatest potential to decarbonise the sector lies with the ability to manage carbon cycles by removing mature trees and decaying forest and crop residues, in order to store the carbon within building materials and products. This would produce compounding benefits, from reducing the risk of forest fires, to increasing the productivity of forested land tracks through rejuvenation and responsible reforestation – thereby increasing the carbon uptake from forests while reducing climate change emissions from the burning of crop waste.

The increased use of properly managed bio-based materials could lead to 40 per cent emission savings in the built environment sector by 2050 in many regions, even as the transition to low-carbon concrete and steel occurs in parallel. Increased demand for decarbonised bio-based materials could increase the carbon uptake of responsibly managed forests in some regions by up to 70 per cent by 2050, compared to baseline scenarios. Supporting the use of all best available technologies will greatly bolster the effort, but substantial research and development is still required to deploy more sustainable methods for bio-based materials. This is especially true in the area of green chemistry for binders, glues and treatments that enable forestry and agricultural by-products to be engineered into structural systems.

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Reducing the extraction of non-renewable materials is further bolstered by the development of circular design for re-use and recycling, alongside the electrification of all processes with renewable energy and the development of at-plant carbon capture and storage to increase material strength by up to 30 per cent in sectors such as cement. Reducing material use through data-driven design optimisation to support the transition to sustainable materials and systems that are derived from renewable bio-based sources such as timber, bamboo and agricultural biomass will require more complex information management and communication across stakeholders. Policies need to support the development of accessible analytical tools, but they also need to mandate their use through building codes.

In pursuing these strategies, there are important co-benefits to consider, as well as risks. In particular, envisioning and implementing a large-scale transition to circular, bio-based materials in the built environment carries substantial risks if the changes to the broader ecological, social and economic context are not planned for and handled very carefully. Decarbonisation of buildings creates risks of unintended consequences to the ecosystems that underpin the production to supply the alternative bio-based materials. It can also lead to the perpetuation or exacerbation of unjust labour practices, and to inequitable shifts in economic gains and losses as industries transition.

The report emphasises the need to take a whole-life cycle approach when assessing strategies to decarbonise emissions from the built environment. When taking such an approach, the work of the geo-biosphere to produce specific local natural resources is valued. Therefore, the use of bio-based and renewable materials such as timber, bamboo and biomass products must be supported with regulations to protect the ecosystems that sustain those resources, with careful consideration of regionally specific, sustainable land use and forest management.

In order to galvanise the market and to enable designers, building owners, and communities to make the right decisions, tools to support the decarbonisation of building materials require more rapid progress. These tools must be supported by access to better quality data and transparent audits conducted by qualified third-party reviewers. More synergy could be leveraged in combining the certification of fair labour and environmental practices / working conditions. In the informal sectors, stakeholders typically have neither the access to data nor the means to conduct analyses or certification, thus greatly disadvantaging both producers and builders in emerging economies from decarbonizing their output, for both local and export markets.

Thus, international cooperation is critical to support fair certification and labelling. Such policies can be synergistic with improving strategies to decarbonise the embodied energy of materials within the formal sectors across the globe, as these are the sectors that are consuming and producing the majority of carbon emissions in the built environment today. Ultimatley the responsibility for galvanising a future net zero economy for the built environment sector should be spread across producers and consumers within the formal global building sector, both public and private.

TABLE 8.1

WHO DOES WHAT TO DECARBONISE MATERIALS?

BUILDING LIFE CYCLE PHASES

	POLICY MAKERS	FINANCIAL INVESTORS + DEVELOPERS	MANUFACTURERS, BUILDERS + WASTE MANAGERS	ARCHITECTS, ENGINEERS + OCCUPANTS
WORK OF THE GEO-BIOSPHERE	> Policies to reduce extraction of non-renewable materials > Facilitate innovation in biodiverse, circular forestry + agriculture	> Use economic practices that value natural capital + biodiversity > Commit to gender equity + fair labour across project lifecycles	> Avoid unsustainable land-use patterns, soil degradation + forestry practices in sourcing both conventional and biomaterials	> Consider the source + recovery rate of non-renewable + renewable materials when designing materials
DESIGN	> Enforce performance based building codes > Develop **fair** green certifications and transparent labeling > Incentivize tools for data-driven design	> Invest in design of recycled, re-used + bio-based materials and components > Invest in accessible data visualization frameworks	> Commit to the development of circular components > Develop materials to optimize recyclability > Develop bio-based alternatives	> Design for longer life > Increase education in decarbonisation strategies > Computation /design / optimization of local materials for re-use
PRODUCTION	> Electrify the grid > Mandate recycling + Best Available Technologies (BAT) > Mandate forest + material management > Improve certifications	> Invest in innovation for low-carbon materials + binders > Invest in new low-carbon methods > Invest in BAT equipment	> Upgrade plants > Avoid primary materials > Circular manufacturing + composites for re-use > Commit to fair labour	> Work with producers to specify circular materials > Design development of alternative biomaterials + components
CONSTRUCTION	> Mandate green certifications > Mandate third party verification of site processes + emissions > Incentivize off-site circular manufacturing	> Increase energy-efficient financing > Improve financing for refurbishment + renovation of existing buildings and materials > Commit to fair labour	> Trace material use > Electrify all equipment with renewable energy > Require energy-efficiency > Improve training > Commit to fair labour	> Manage on-site waste through pre-fabrication > Improve management of on-site construction with circular design
USE	> Building energy codes that mandate material selection for high-performance building envelopes to reduce operational carbon > Incentivize renovation over new construction	> Financial tools to incentivize low carbon material selection by reconizing energy + cost pay back periods	> Support building owners + occupants to select low carbon alternatives through supply chain development	> Increase material life with low-carbon maintenance practices > Select materials that reduce operational carbon
END OF USE	> Certify pre-used components > Building codes to mandate re-use > City planning of transfer plants > Regulate demolition	> Provide economic incentives to avoid demolition by refurbishing buildings, increasing re-use + recycling	> Improve recovery + on-site sorting of materials > Standardize materials to improve recycling	> Design for Dissasembly + Re-Use > Increase continuing education for students + professionals in novel circular material strategies

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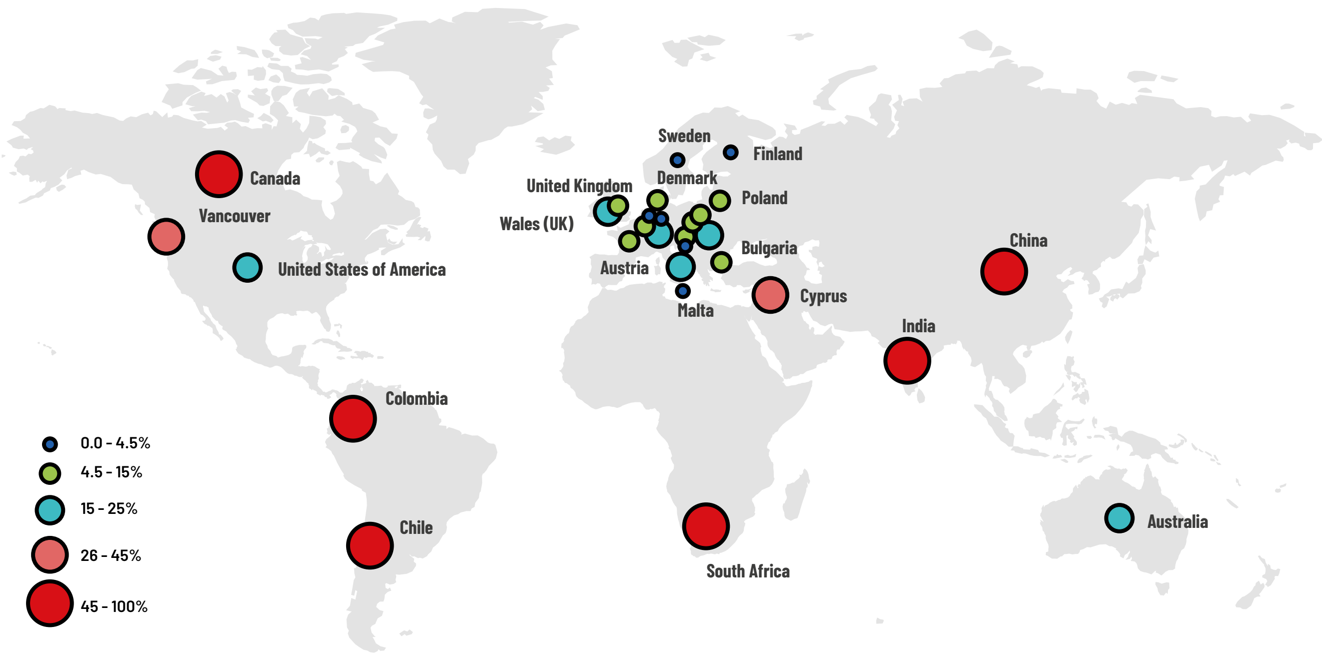
Annexes

ANNEX 1
CONSTRUCTION, RENOVATION AND DEMOLITION WASTE

Figure A.1 Share of construction, renovation and demolition waste sent to landfill in selected countries



European countries have low shares of landfilling and high shares of waste recovery.

Note: The red circles in the figure indicate countries with the highest rates of landfill. The blue circles indicate countries with a closed-loop system, with low landfill rates and high shares of recovery (i.e., re-use, recycling, or incineration for energy recovery). Source: Chen et al. 2022.

ANNEX 2

"RE-INVENTING" CEMENT IS CRITICAL

Cementitious binders are an essential precursor to both concrete and mortar, with cement acting as a glue for aggregates and water to form a brittle and typically strong building material. Cementitious binders typically comprise hydraulic cement and supplementary cementitious materials in different proportions. Hydraulic cements bind the aggregates through a chemical reaction that is triggered by the addition of water. The most common example of hydraulic cement is "ordinary Portland cement."

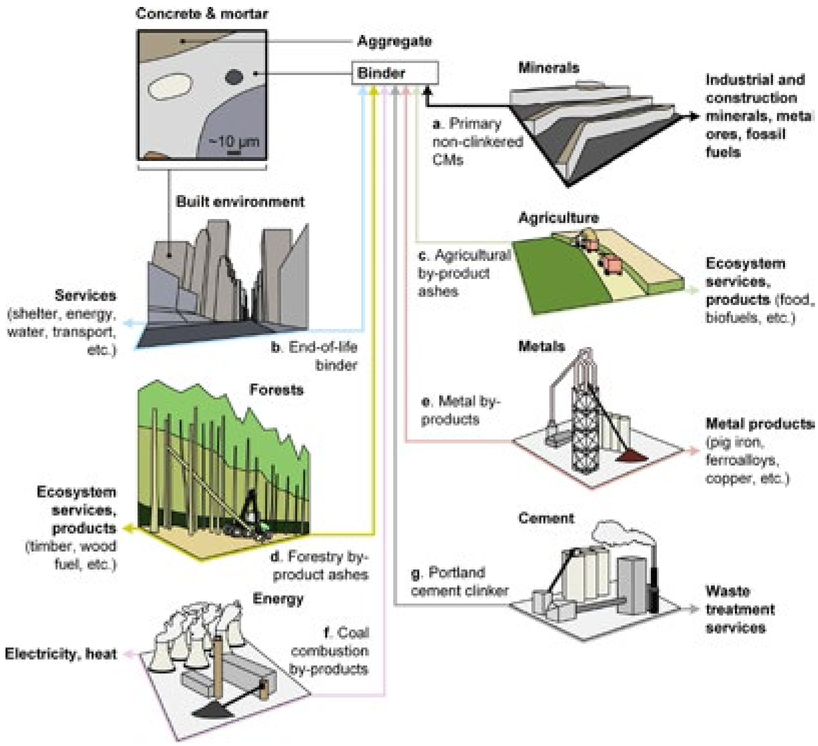
Producing Portland cement involves three main steps: preparing the material (extraction, crushing, pre-homogenisation and raw meal grinding), producing the clinker (preheating, precalcining, clinker production in a rotary kiln at temperatures of 1,450 degrees Celsius), and grinding the clinker (mixing or blending the ground clinker with gypsum and other components to produce cement) (IEA 2018a).

In concrete mixtures, supplementary cementitious materials are used, together with ordinary Portland cement, as extenders to improve the properties of fresh and hardened concrete, or to reduce the carbon footprint of the cementitious binder (American Concrete Institute 2022). The properties of the finished cement depend on the ratio and selection of the blending materials, which can broadly be classified as primary versus secondary cementitious materials (Shah et al. 2022).

Primary cementitious materials include limestone, natural volcanic materials, and kaolinite and calcined clays (including calcined clay limestone or LC3) (Scrivener et al. 2018a), while secondary cementitious materials include industrial by-products such as coal fly ash and steel blast furnace slag. They also include bio-based ashes (mostly by-products from agriculture, such as rice husk or cassava peel, as well as from forestry) and end-of-life materials (mostly binder from construction and demolition wastes, but also pozzolans from recycled glass) (see **Figure A.2**).

The type of supplementary cementitious material that can be used depends on the local context (see **Figure A.3**), such as the plant capacity, the moisture content and burnability of the raw materials, the availability of blending materials, the reliability of supply chains, as well as national cement standards. However, a major impediment to widespread adoption of many alternative, "circular," secondary cementitious materials, particularly the bio-based options, is the variable performance and lack of local certification.

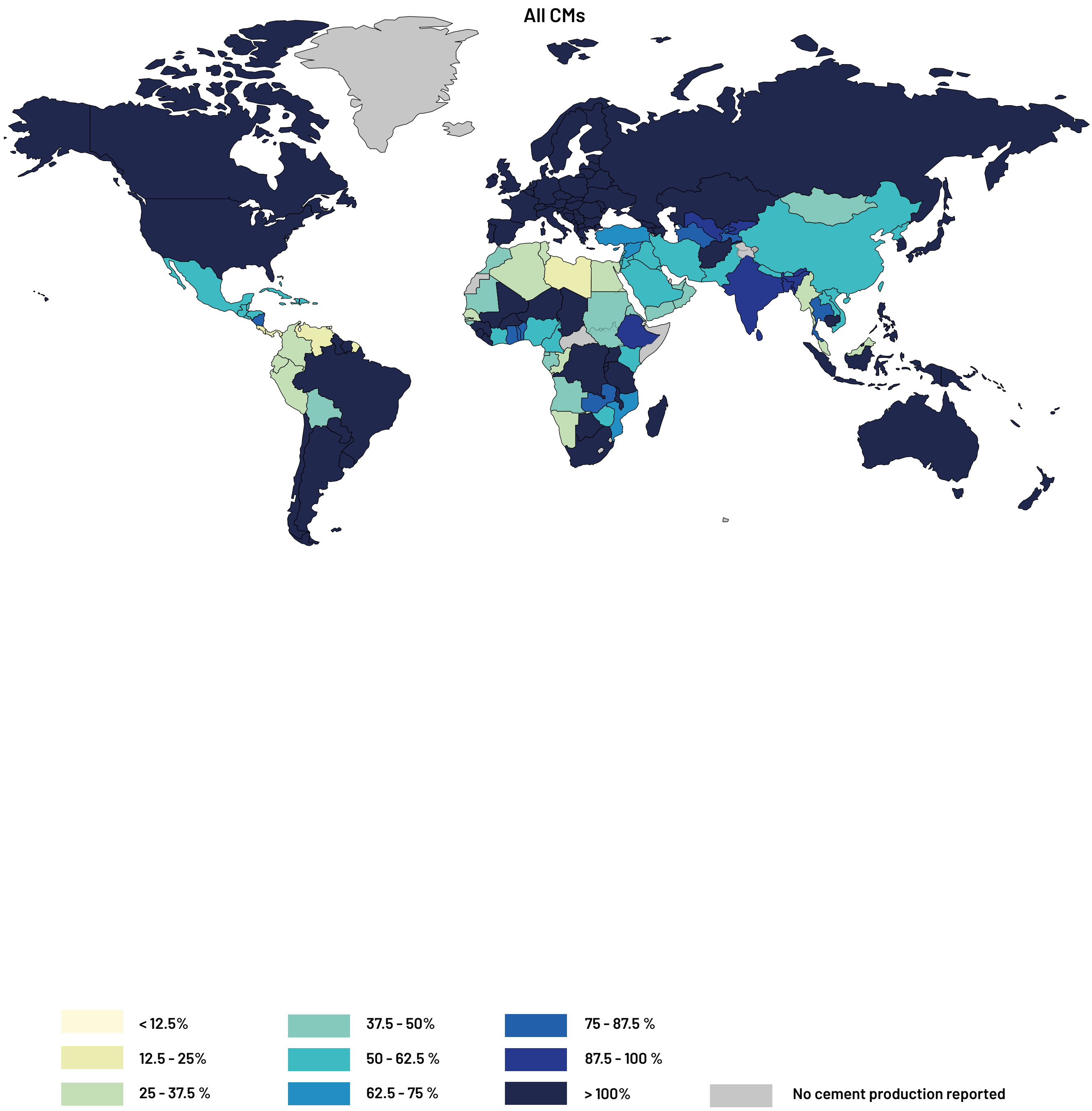
Figure A.2 Emerging alternative cementitious binders



European countries have low shares of landfilling and high shares of waste recovery.

Note: The red circles in the figure indicate countries with the highest rates of landfill. The blue circles indicate countries with a closed-loop system, with low landfill rates and high shares of recovery (i.e., re-use, recycling, or incineration for energy recovery). Source: Chen et al. 2022.

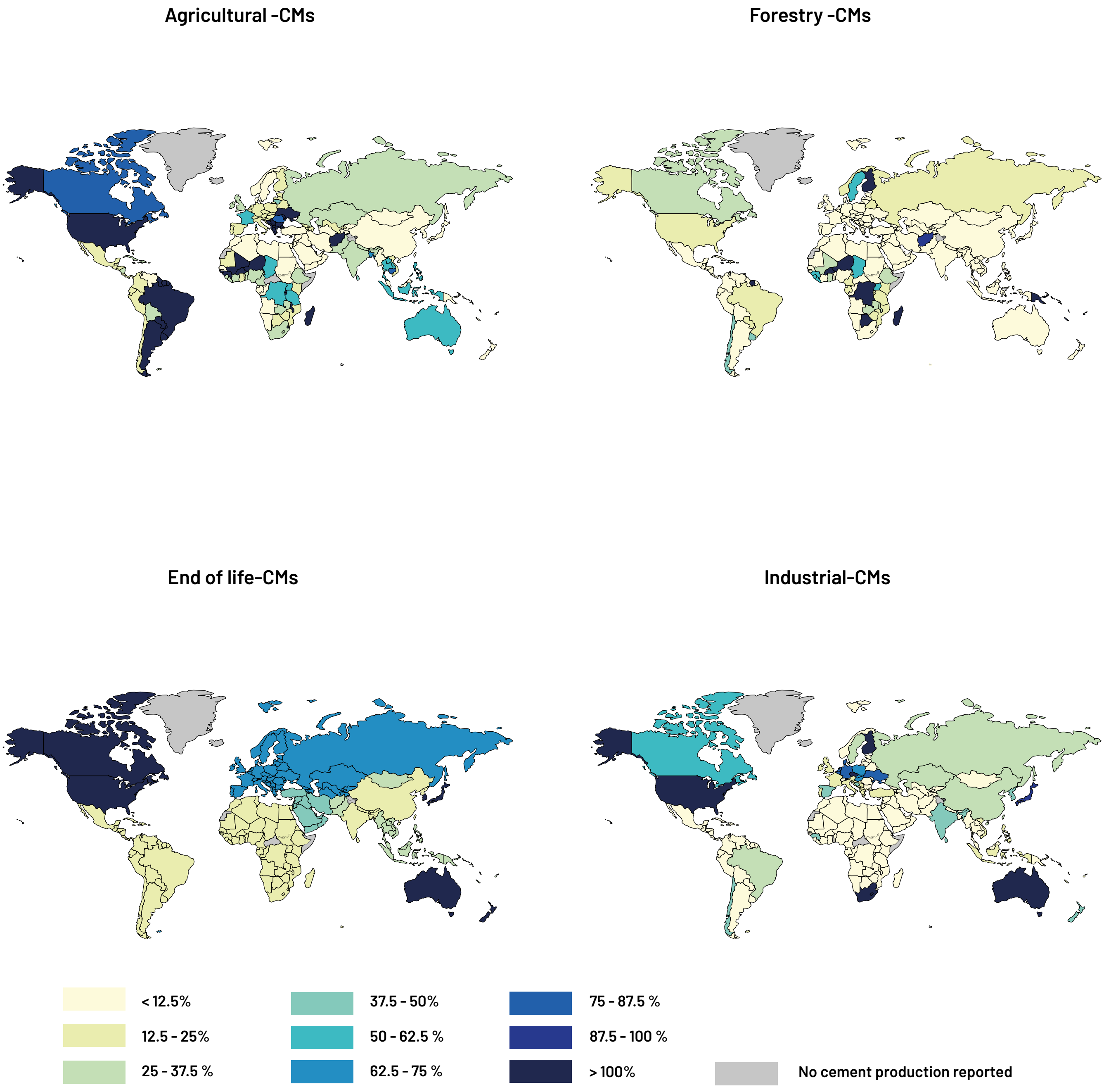
Figure A.3a Availability of alternative cementitious binders by region, 2018



Most countries could generate sufficient secondary cementitious materials to substitute for Portland cement.

Source: Shah et al. 2022.

Figure A.3b Availability of alternative cementitious binders, by region and type, 2018

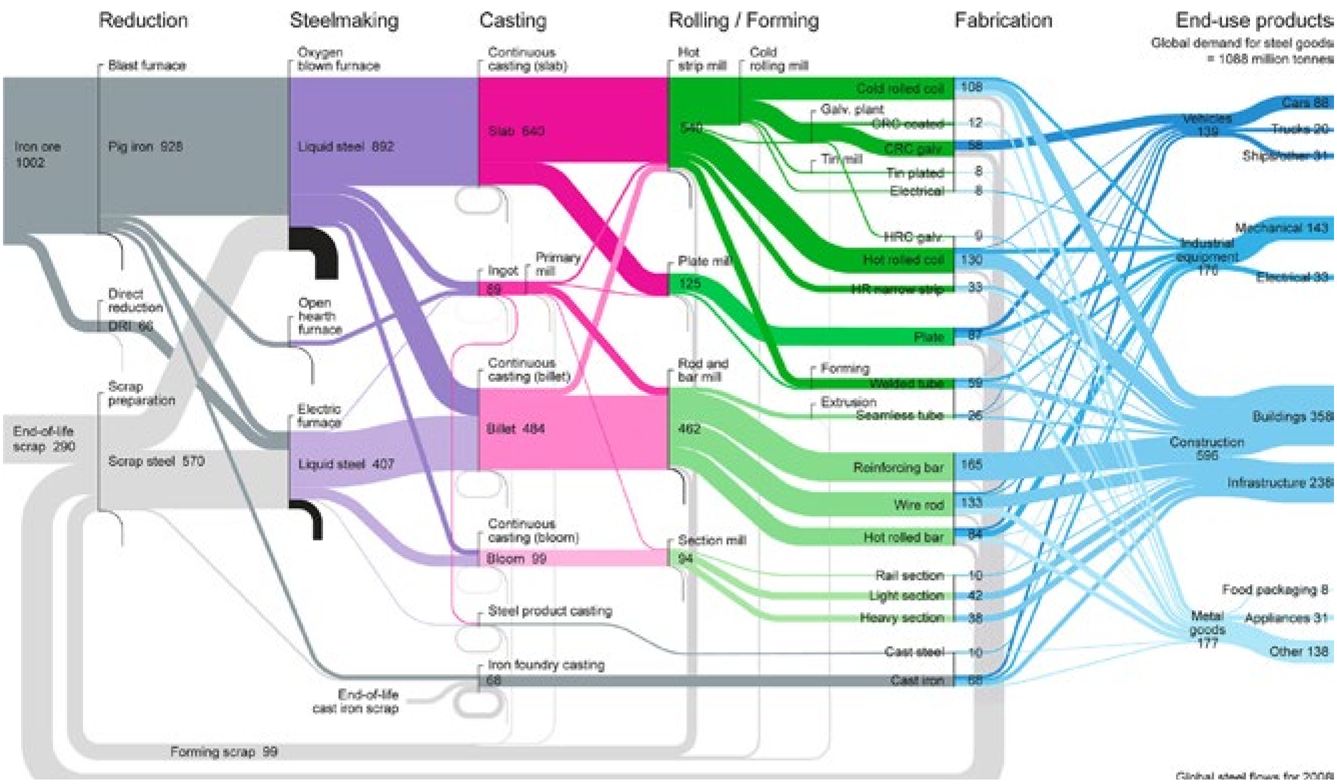


Source: Shah et al. 2022.

ANNEX 3

MATERIAL FLOWS FOR STEEL, ALUMINIUM AND GLASS

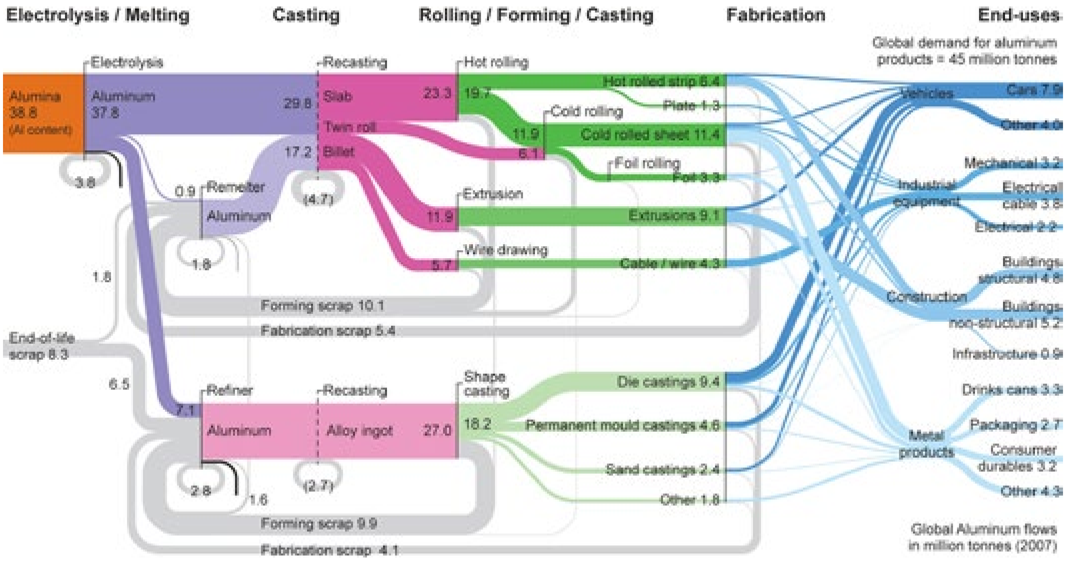
Figure A.4 Steel material flows



More than half of the world's steel is used in the construction of buildings and infrastructure.

Note: Circular material flows dominate post-fabrication, with little returning into the global flow of steel after end-use products. Source: Cullen, Allwood and Bambach 2012.

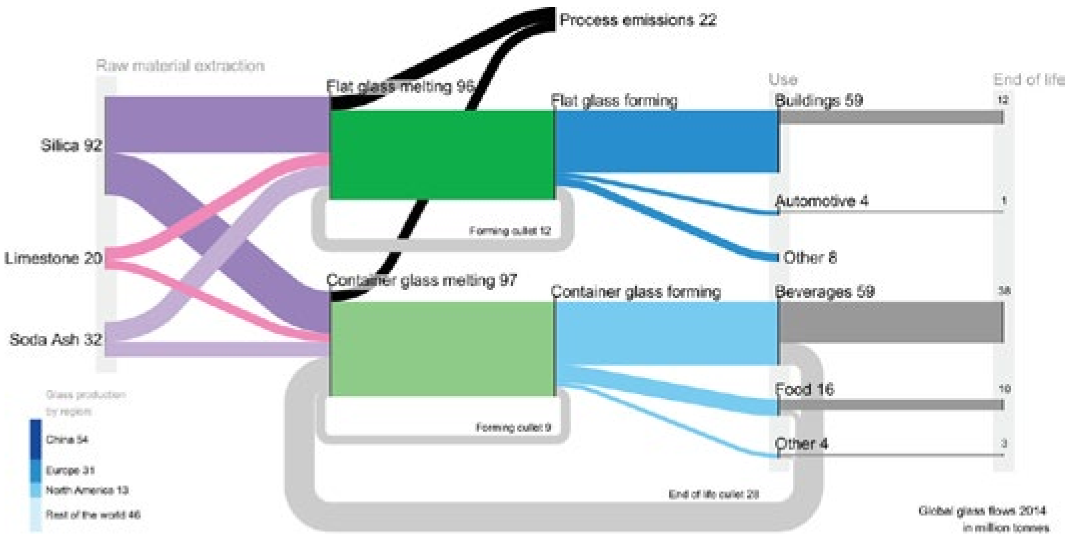
Figure A.5 Global flows of aluminium, 2007



Aluminium is produced using primary mined materials and, to a lesser extent, scrap.

Note: The figure shows the flow of aluminium from production (ore-based, top, and scrap-based, bottom, grey flows) to end uses, with the construction and associated sectors highlighted..

Figure A.6 Global material flow and end uses of glass



Global glass production is divided into container glass (for food and beverages) and flat glass.

Source: Westbroek et al. 2021.

ANNEX 4

COUNTRY CASE STUDIES OF THE "AVOID-SHIFT-IMPROVE" STRATEGIES

Globally, countries with very different built environment contexts can pursue decarbonisation of their built environment sectors using the "Avoid-Shift-Improve" strategies.

CANADA

Dominant materials:

- Concrete and steel (commercial)
- timber (residential)

Current status:

- Canada has one of the cleanest grids for global manufacturing (82 per cent emissions-free) and uses more than 70 per cent less carbon than the global average for steel and aluminium (Environment and Climate Change Canada 2022). However, the electricity is mostly from hydropower, and further proposed expansion of dams is being challenged for degrading environmental and indigenous rights.
- Timber is re-emerging to replace concrete and steel in the residential sector, and there are world-first demonstrations for massive timber use in high-rise construction, but further development of sustainable binders is necessary.

Policy recommendations:

AVOID primary materials and move to a circular economy

- Construction represents a core sector for advancing the circular economy in Canada due to its economic importance, high material necessity and large quantities of waste (Council of Canadian Academies 2021).

SHIFT to bio-based materials

- Improve sustainable forestry practices if wood resources are to be more in demand.
- Use a mix of timber species to avoid a monoculture in forestry (for example, white spruce monocultures have replaced Acadian forest, leading to reduced biodiversity, diminished ecosystem function and negative cultural impacts for Indigenous people (Government of Canada 2021).
- Mandate increased use of agricultural cover crops and by-products for building materials.

IMPROVE conventional materials and processes

- Establish a Clean Infrastructure Challenge Fund to promote public procurement and demonstration of decarbonisation practices.
- Promote local, Canadian-made products such as Portland limestone cement, which contains up to 10 per cent less embodied carbon than imported cement and would avoid more than 1 million tons of carbon pollution each year.

FINLAND

Dominant materials:

- Concrete
- Timber and wood (residential)

Current status:

- Has reduced its emissions at a faster pace than the European Union average since 2005, with the largest reductions in manufacturing industries and construction. The sector's share of total emissions fell from 16 per cent in 2005 to 11 per cent in 2019 (Jensen 2021).
- Has some of the world's most ambitious building codes that support the transition to bio-based materials and net zero urban emissions.
- Initiated the use of neighbourhood-level carbon planning tools (AVA).

Policy recommendations:

AVOID primary materials and move to a circular economy

- Adopt policies and targets at the municipal and national levels for integrated decarbonisation across multiple scales of infrastructure and buildings.
- Use carbon tracking tools at the level of urban planning and regional ecosystems.

SHIFT to more sustainable bio-based materials

- Further develop sustainable forestry practices, as wood resources are in high demand, but overharvesting of raw timber needs to be replaced with more sustainable practices.
- Scale up the development and use of agricultural cover crops and by-products for building materials.

IMPROVE conventional materials and processes

- Improve data collection methods for building materials and processes, especially to promote re-use of materials.
- Build systems to collect data on operational energy costs and create platforms for users to track energy costs of material decisions.

GHANA

Dominant materials:
- Concrete masonry
- Metals (roofing)

Current status:
- The share of concrete masonry used for external wall construction has risen from 39 per cent to 64 per cent since 2000 (Ghana Statistical Service 2021).
- Metal sheets comprise 80 per cent of all housing roofing applications (Ghana Statistical Service 2021).
- Use of low-carbon earth masonry for wall construction declined 50 to 30 per cent since 2000 (Ghana Statistical Service 2021).
- Timber logging is an estimated two to three times above the legal annual allowable cuts set by the Ghana Forestry Commission (Oduro 2016).
- The electricity sector has shifted sharply from 64 per cent hydropower in 2015 to 66 per cent fossil fuel-based in 2020 (Ritchie, Roser and Rosado 2020).

Policy recommendations:

AVOID primary materials and move to a circular economy
- Invest in and market local building materials, with a focus on the partial or full substitution of concrete masonry products as well as improved infrastructure to recover high rates of local material waste in the timber and agricultural sectors.
- Provide research support and industrial incentives to encourage the use of locally available and low-carbon alternatives to Portland cement binders in concrete masonry products.

SHIFT to bio-based materials
- Progressively revise local building codes and standards to include near-term installation and performance guidelines for low-carbon, bio-based and earth masonry materials.
- Revise the building permit process to require mandatory minimum values for roofing insulation.
- Provide professional training and upskilling in the use of low-carbon, bio-based and earth building materials across the agriculture, manufacturing, design, construction, artisanal and waste management sectors.

IMPROVE conventional materials and processes
- Progressively revise local building standards and codes to include material specifications for embodied carbon and climate performance.
- Enact green procurement policies that support the use of low-carbon and locally available bio-based alternatives as aggregates, binders, reinforcing components or additives across masonry and timber products.

GUATEMALA

Dominant materials:
- Concrete block and steel
- Earth-based and biomass materials (vernacular traditions)

Current status:
- In Guatemala's booming residential construction sector, between 2002 and 2018, the use of cement block increased 96 per cent, concrete 215 per cent and metal 191 per cent; meanwhile, the use of traditional mud declined 38 per cent and the use of agricultural and forest by-product materials (straw, sticks, or canes) fell 29 per cent (Guatemala INE 2002).

Policy recommendations:

AVOID primary materials and move to a circular economy
- Establish national building codes with regional compliance, and progressively revise local building standards and codes to include embodied carbon and climate performance.
- Support national and regional schools in architecture, engineering and industrial design to focus on the transition to circular principles for modular pre-fabricated concrete components, and encourage design for disassembly and re-use of components.

SHIFT to bio-based materials
- Develop standards and conduct certifications of regional and traditional earth-based and bio-based structural and additive materials based on local species, to engender confidence in these materials for multi-storey construction among builders who need to densify urban settlements.
- Facilitate cooperation among small, local and large-scale cement industry players and regional agricultural producers in developing novel (bio-based) concrete admixtures to reduce binder requirements, while also capitalising on and upcycling problematic biowaste from regional agriculture.
- Develop standards for production and regulation of regional bamboo, forest by-products and biomass.

IMPROVE conventional materials and processes
- Facilitate domestic partnerships with multinational producers towards establishing net zero cement production based on best available technologies by electrifying with renewables.
- Capitalise on the regional momentum of CEMEX and others towards further research and demonstration of carbon capture and storage at cement manufacturing plants, with renewable electrification.

INDIA

Dominant materials:

- Bricks, concrete and steel
- Rammed earth and mud brick (rural areas)

Current status:

- India's green building market doubled in the four years between 2018 and 2022, driven by increasing awareness level, environmental benefits and government support.
- Bricks and traditional materials still play a significant role in rural areas, but with rapid urbanisation, cement and concrete have become the most commonly used construction materials in India, accounting for over 80 per cent of the total.
- The Indian government has launched several initiatives to promote sustainable and eco-friendly building materials, in order to use secondary cementitious materials such as fly ash in bricks and green concrete.
- Women comprise only 12 per cent of the building sector workforce, mostly in the least desirable jobs in the informal sector, with a gender pay gap of between 30 and 40 per cent.
- The use of pre-fabricated construction materials is gaining popularity in the country due to the higher material efficiencies and lower on-site emissions and disruption.

Policy recommendations:

AVOID primary materials and move to a circular economy

- Establish enforced policies that require companies to use recycled materials in their production processes and to design products for re-use or recycling, which would reduce waste and resource consumption.

SHIFT to bio-based materials

- Address supply chain challenges by promoting upcycling of waste from food crops that can be used as bio-based materials and by encouraging investment in the processing and manufacturing infrastructure for biomaterials.
- Focus on local needs by supporting research and development of bio-based materials that address specific challenges faced by communities in India; address negative perceptions through design and marketing.

IMPROVE conventional materials and processes

- Strengthen environmental regulations to reduce greenhouse gas emissions and resource consumption in the manufacturing sector using regulations on energy efficiency, water use and waste disposal.
- Implement tax incentives and subsidies for companies that use low-carbon materials in their production processes.

PERU

Dominant materials:

- Concrete and steel (urban housing)
- Earth-based materials and bio-based materials (rural housing)

Current status:

- In urban and rural areas, there is a shift towards concrete and steel construction, replacing traditional adobe, mudwall, wood and cane buildings. These new construction techniques often do not respond to local climate and building traditions. Seismic construction is a crucial consideration.
- Around 66 per cent of residential construction in Peru is in the informal sector (Espinoza and Fort 2020), which in the consolidation phase employs mineral-based materials.

Policy recommendations:

AVOID primary materials and move to a circular economy

- Incentivise the adaptive re-use of existing buildings and use of circular materials with better credit systems and labels.
- For the informal housing sector, support the participation of architects and engineers and the training of local populations in topics such as design for disassembly and the use of low-impact and local materials.
- Support digitalization as an opportunity to reduce waste production (currently used mainly in large projects).
- Local governments should prioritize the research and development of design for disassembly strategies for structural elements.

SHIFT to bio-based materials

- Promote sustainable construction practices by employing biodegradable biomaterials and prioritizing sourcing raw biomaterials while preserving vernacular architecture in rural areas.

IMPROVE conventional materials and processes

- Encourage research and development to transition traditional seismic materials towards lower emissions and re-evaluate local construction techniques through technology transfer.
- Support job creation opportunities at the end-of-use phase, from formalising existing recyclers to creating new, formal jobs related to the construction industry.
- Implement more transfer plants in cities and allow urban landfills to receive construction, renovation and demolition materials, to prevent illegal dumping sites.
- Improve certifications, credits and labels.

SENEGAL

Dominant materials:
- Concrete masonry
- Metal (roofing)

Current status:
- Concrete masonry in Senegal accounts for nearly 70 per cent of wall construction and 71 per cent of roofing materials (PEEB 2021b).
- Metal sheets (38 per cent) are slightly more prevalent than concrete masonry (32 per cent) in rural roofing assemblies (ANSD 2021)
- Only 5 percent of local timber demand is met by local production, from threatened tree species (Berthome, Silvertre and Kouame 2013).
- Although fossil fuels supply 86 percent of electricity, the supply from renewable sources has increased (6 percent hydropower, 6 percent solar, 0.33 per cent wind and other renewables) (Ritchie, Roser and Rosado 2020).

Policy recommendations:

AVOID primary materials and move to a circular economy
- Progressively revise local building standards and codes to include embodied carbon and climate performance.
- Provide research support and industrial incentives to encourage the use of locally available and low-carbon alternatives to Portland cement binders, including supplementary cementitious materials to improve the stabilisation and hygrothermal performance of masonry products.

SHIFT to bio-based materials
- Invest in locally available low-carbon fuels for cement production.
- Enact government mandates promoting the use of local bio-based and earth masonry in green public procurement projects.
- Educate finance and insurance companies working in the building sector about the positive impacts of low-carbon buildings, and pro-actively incentivise building owners who adopt such technologies, in association with standards such as the Africa Research and Standards Organisation's recently ratified compressed earth block standard (ARSO 2018).

IMPROVE conventional materials and processes
- Promote finance and industrial investment in the research and development of technological innovation of cement, metal and timber products that are consistent with low greenhouse gas emissions and resilient local building material sectors.

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