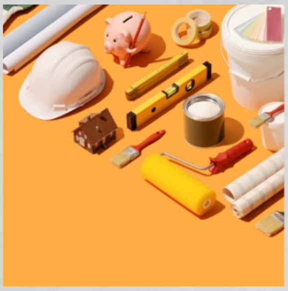
building 4.0 crc

#48: Scoping Study for Building the Future – Circular Economy

FINAL REPORT



Australian Government
Department of Industry, Science and Resources

Cooperative Research Centres Program

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ABBREVIATIONS

Institutions

ABCB	Australian Building Codes Board
ACE	Australian Circular Economy
ASBN	Adelaide Sustainable Business Network
BREEAM	Building Research Establishment Environmental Assessment Methodology
CEFC	Clean Energy Finance Corporation
CSIRO	Commonwealth Scientific and Industrial Research Organisation
GBCA	Green Building Council of Australia
GECA	Good Environmental Choice Australia
GISA	Green Industries South Australia
GRESB	Global Real Estate Sustainability Benchmark
IPCC	Intergovernmental Panel on Climate Change
ISSB	International Sustainability Standards Board
MECLA	Materials and Embodied Carbon Leaders' Alliance

Technical words

AI	Artificial intelligence
BIM	Building Information Modelling
C&D	Construction and Demolition
CE	Circular Economy
CLT	Cross-Laminated Timber
CO_2	Carbon dioxide
EPD	Environmental Product Declarations
ESG	Environment, Social and Governance
ESP	Environmentally Sustainable Procurement
FAHP	Fuzzy Analytic Hierarchy Process
GDP	Gross Domestic Product
I4.0	Industry 4.0
IIoT	Industrial Internet of Things
IoT	Internet of Things
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCSA	Life Cycle Sustainability Assessment
LEED	Leadership in Energy and Environmental Design
LVL	Laminated Veneer Lumber
Mt	Million tonnes
NABERS	National Australian Built Environment Rating System
NCC	National Construction Code

NatHERS	Nationwide House Energy Rating Scheme
PPA	Power Purchase Agreement
PVC	Polyvinyl Chloride
ResCom	Resource Conservative Manufacturing
RFID	Radio-Frequency Identification
S-LCA	Social Life Cycle Assessment
TCFD	Task Force on Climate-related Financial Disclosures

GLOSSARY

Building information modelling (BIM) is a process of generating and managing digital representations of the physical and functional aspects of places. BIM provides underlying information to support tools, technologies, and contracts.

Certification schemes are standards for entire structures or substructures to rate energy and water systems. They are complementary tools for identifying cost savings and future improvements and are independently verified by industry bodies prior to awarding a level of certification.

Circular economy (CE) is a system that calls for production and consumption to function within a closed loop whereby the life cycle of the product is extended. The concept of CE typically draws on principles to achieve sustainable development by mitigating waste and realising value from the built environment and portfolio assets, preventing depletion of resources and regenerating nature (Ellen MacArthur Foundation, 2013). The ISO Standard 59004 defines CE as an 'economic system that uses a systemic approach to maintain a circular flow of resources, by recovering, retaining or adding to their value, while contributing to sustainable development' (ISO, 2024, p.1).

Decarbonisation is a process to reduce greenhouse gas emissions (GHGs).

Digital engineering converges data software technologies, such as BIM, geographic information systems (GIS), and related analysis systems and tools, to foster better business, project and asset management outcomes.

Digital twin is a technology that aggregates data and digital models from sources to generate a 3D or 4D model of a building, precinct, or city for planning and modelling, which has a one-to-one correspondence with the physical asset within the scope of the area of interest.

Eco-design strategies are methods for designing, constructing or upgrading buildings that maximise environmental performance, reduce material use and waste, and/or improve productivity.

Environmental footprint measures the impact of individuals, organisations, or countries on the environment. It quantifies the amount of natural resources consumed and waste generated compared with the Earth's ability to regenerate those resources.

Embodied carbon is the carbon emission generated during the manufacture, construction, use, maintenance and demolition of buildings. Global warming potential is the metric used to measure and track embodied carbon. Global warming potential is quantified in kilograms of CO_2 equivalent (kg CO_2e).

Embodied energy is the energy consumed by all the processes associated with building, from mining and processing natural resources to manufacturing, transport and product delivery.

Extended producer responsibility is a policy that imposes responsibility on the manufacturer for a product at its end of life.

Green bonds are a form of investment to finance new and existing projects that provide climate change and environmental benefits.

Land use planning refers to development, usually at the state or local government level, incorporating policies and regulations to guide urban change and determine future land use. It involves the coordination of private and public investments and community engagement and aims to mitigate potential negative impacts of developments while enhancing beneficial outcomes for the community.

Landfill levy is a tax applied at differential rates to municipal, industrial, and prescribed waste disposed of at licensed landfill operators.

Life cycle encompasses the stages of a product, from design to raw material extraction, production, distribution, use and end-of-life management. At post-consumption, options to return, reuse, restore, recycle, repair, remanufacture and recover are considered over landfill disposal. Reuse and refurbishment are preferred or mandated for heritage structures in buildings.

Linear economy is an economic system where resources typically follow the pattern of extraction, production, use and disposal.

Material Circularity Indicator measures the restoration of material flows and the intensity of material circulation for a company or product using indicators—inputs in the production process, utility during the use phase, destination after use and efficiency of recycling (Ellen MacArthur Foundation, n.d.).

Material passport is an inventory stored in a database of the products, systems and materials contained within an asset.

Material recycling can involve downcycling to convert materials into new materials of lesser quality and reduced functionality or upcycling to convert materials into new materials of higher quality and increased functionality.

Modular design is manufacturing building components in a factory or off site prior to transporting and assembling them at a project site.

Operational carbon, distinguished from embodied carbon, is the amount of carbon emissions emitted during a building's in-use phase, usually measured over a specified time interval.

Operational energy is the energy that is required for a structure to function during its entire service life. It includes all heating, ventilation, air conditioning (HVAC), lighting and building appliances.

Planetary boundaries are the limits within which humanity can safely operate to avoid causing significant harm to the Earth's system. Nine planetary boundaries are defined: climate change, biodiversity loss, biogeochemical flows, ocean acidification, land-system change, freshwater use, atmospheric aerosol loading, introduction of novel entities and stratospheric ozone depletion (Rockström et al., 2009).

Product stewardship schemes place responsibility on parties who produce, sell, use, or dispose of products to reduce their impact on human health and the environment.

Reverse logistics are supply loops that refer to setting up a system of forward and backward processes to facilitate material, or product flows from inputs of raw materials, production, finished goods and end-of-use back to raw materials, joined with intermediate steps to prolong the material or product life cycle.

Sustainable development is development that meets the environmental, social and economic needs of the present without compromising the ability of future generations to meet their own needs.

Scope 1 emissions are direct GHG emissions from sources controlled or owned by an organisation.

Scope 2 emissions are indirect GHG emissions related to purchasing electricity, steam, heat, or cooling.

Scope 3 emissions result from activities and from assets not owned or controlled by a reporting organisation but that the organisation indirectly impacts within its value chain.

Smart cities apply information and communication technologies to reshape the urban fabric by acquiring data about a particular built or natural environment and then using it to understand and, if appropriate, control what is happening there. Buildings may incorporate state-of-the-art technology to collect data and deliver intelligent feedback for responsive mechanisms.

Urban design concerns producing and adapting the appearance and function of the built environment. Beyond an individual building, it focuses on the space and relationship between buildings and surroundings and embeds societal and cultural values to shape social behaviour, and includes macro factors, such as traffic flows, noise, urban heat.

Urban renewal is an intervention to redevelop an established area, generally to improve neighbourhood amenities in underutilised or disadvantaged metropolitan areas.

Value chain includes parties linked upstream and downstream in processes and activities that deliver product value to an end user.

EXECUTIVE SUMMARY

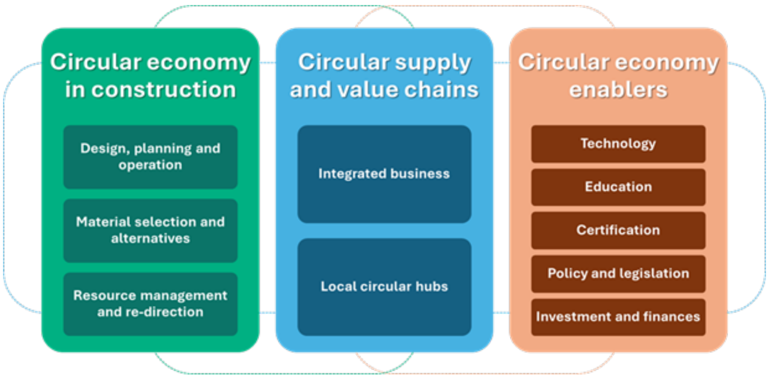
The built environment is central to our modern lifestyle and wellbeing, is essential for productivity and learning, fosters social interaction and community, and has cultural and aesthetic value. Housing provides shelter and safety, contributes to health and wellbeing, and has a pronounced economic impact. However, the built environment has both positive and negative impacts on environmental, economic and social sustainability.

The built environment impacts the natural environment via material extraction, land use change, freshwater use, greenhouse gas emissions and pollution as well as waste generation. It is well-known that resources are extracted from the Earth system at an unsustainable rate and that humanity is already operating outside of some environmental limits as defined by the planetary boundaries framework.

The circular economy concept describes an economic system that addresses sustainability by eliminating waste, establishing the continual use of resources and the regeneration of nature. However, the transition from the traditional linear economy, which follows a 'take, make, use, dispose' model, is challenging. The circular economy literally operates in a circle, which means every stakeholder within the circle depends on the actions of the other stakeholders. Importantly, if stakeholders shift environmental or economic burdens to other stakeholders, the circle is in danger of breaking and the circular economy system will collapse. Therefore, the circular economy relies on genuine collaboration and partnership along the circular supply and value chain.

Although a conscious use of material is important in establishing a circular economy, the focus cannot just be on material use, waste and recycling. Importantly, there should be a focus on other non-material circular economy principles, such as designing-out overconsumption and pollution as well as regeneration. Non-renewable and renewable materials need to be used in smarter ways to create a more sustainable impact.

While this final report on 'Building the Future – Circular Economy' and the developed roadmap concentrates on the establishment of a circular economy for buildings, the learnings and roadmap can also be applied to public infrastructure (such as roads and bridges), open spaces, and utilities and services. The roadmap towards a circular economy within the Australian building and construction sector presented in this report was developed by engaging with stakeholders along the circular supply and value chain via co-design workshops, interviews and site visits and was complimented by a literature and market review. While developing the roadmap, we focused on the circular economy concepts of Narrow (use less), Slow (use longer), Cycle (use again), and Regenerate (make clean).



The developed roadmap has three key themes: Circular economy in construction, circular supply and value chains, and circular economy enablers. Each key theme is then subdivided into sub-themes. Recommendations of actions for each sub-theme are provided alongside non-exhaustive tool examples supporting the implementation of a circular economy by the stakeholders.

In addition, this report highlights key gaps and future research areas that require further investigation and more detailed observation to support the CE transition and propose future phases of research to implement the circular strategic action plan for building the future and enacting long-term and lasting change.

PROJECT OVERVIEW

Project #48 provides an in-depth analysis of the transition to a circular economy (CE) within the Australian building industry. The project summary diagram in Figure 1 shows a high-level overview of activities performed during Project #48. It captures the project's background and rationale, opportunities and suggested solutions, along with the goal, methods employed and key findings and themes. The primary aim of this scoping study was to develop a roadmap and offer recommendations and future research areas to guide the Australian construction and building industry and its stakeholders toward sustainable CE practices and strategies. The components presented in the summary diagram are elaborated in the following sections.

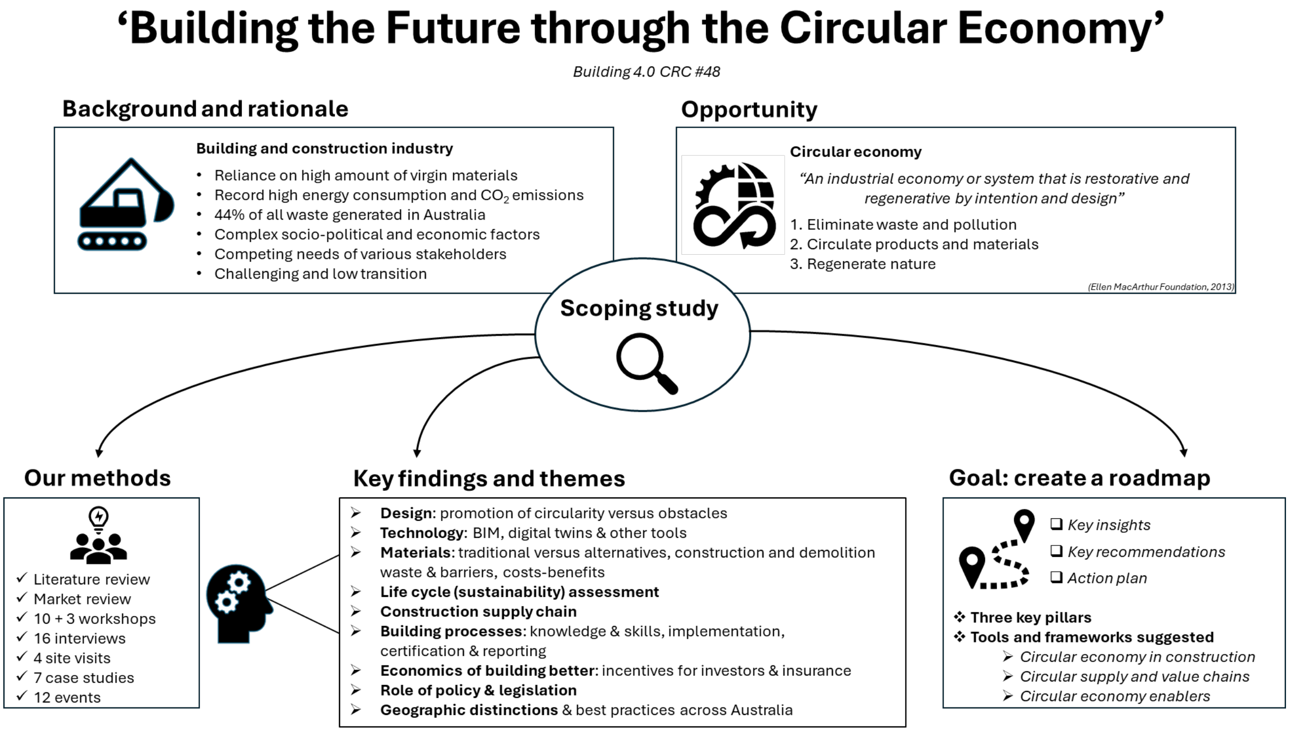


Figure 1. Project summary diagram
Source: Own elaboration

Towards a roadmap

The roadmap proposed in this study aims to address how interventions can be applied to scale circular practices through holistic strategies. It should be viewed as a mandate for change that intertwines ambition, realism and a sense of optimism for the future.

Aiming for knowledge exchange, professional development and advocacy for change, this scoping study project was funded by the Building 4.0 Cooperative Research Centre (CRC), the Queensland University of Technology and nearly twenty university and industry partners to create a roadmap for ***'Building the Future through the Circular Economy'***. The project findings and the resulting roadmap will be widely disseminated to study participants, industry stakeholders and the government to catalyse meaningful action. The objectives are:

1. To present a meaningful and tangible definition of circularity for Australian Property and Construction businesses and those connected to the built environment supply value chain.

2. To determine enablers and barriers to circularity, how far from the CE the sector is and how transitioning to a CE will help to achieve zero emissions and meet environmental, social and governance (ESG) goals.

3. To identify the parameters of a business case of individual stakeholders and develop a sector-specific roadmap for achieving circularity by understanding:

    a. Benefits, costs, opportunities, challenges and priorities for implementing new circular models;
    b. Roles of business, government and academia in bringing strategies to action;
    c. Investment required by those key groups for resilience and other significant benefits; and
    d. Stakeholder training, knowledge gaps and opportunities to facilitate practical translation of strategies into actions to achieve circularity.

Background and rationale

In Australia, construction and building processes heavily rely on virgin materials (251 Mt per year) and they are among the most resource-intensive industries. They also contribute to high energy consumption and CO_2 emissions and generate 25 Mt of C&D waste. These factors underline the potential for developing new solutions and building components that minimise the use of virgin materials and material waste and offer significant positive environmental impacts.

Construction is one of the largest sectors in today's global economy and its evolution is a complex process (Maskuriy et al., 2019). Construction serves as a significant employment generator in numerous countries (Karmakar & Delhi, 2021) and is closely linked to overall economic development (Elghaish et al., 2022). For example, it represents 13% of GDP and employs 7% of the world's working-age population (Barbosa et al., 2017). However, the industry operates within a linear economy and it exposes stakeholders to various risks, such as high resource prices and supply disruptions (Elghaish et al., 2022). In addition, the linear processes have an adverse impact on the environment, resulting in destruction of nature, air pollution and other hazards (Sun et al., 2021).

In particular, the industry and its construction and demolition (C&D) processes stand out as the most resource-intensive in the world, consuming nearly a third of all materials, contributing to a third of global waste and accounting for over 34% of global energy demand with an estimated 37% of energy- and process-related CO_2 emissions (Elghaish et al., 2022; UN Environment Programme, 2022). Despite an increase in energy efficiency investment and lower energy intensity, the building and construction sector's energy consumption and CO_2 emissions rebounded to a record high following the COVID-19 pandemic (Tollefson, 2021).

The industry's high energy consumption and substantial reliance on Earth's renewable and non-renewable resources (Ngowi et al., 2020) raises concerns about its sustainability and growth. The environmental implications are further exacerbated by the rapid expansion of the industry, which is driven by the rise in urban populations and an increasing demand for housing and infrastructure (Maskuriy et al., 2019). If the world population reaches 9.6 billion by 2050, nearly three Earths will be needed to provide sufficient natural resources to sustain our current lifestyles (United Nations, 2021) if no significant actions are taken to minimise consumption or if overconsumption of non-renewable resources is not addressed efficiently. The increasing population pressures during the pandemic recovery are also expected to underpin strong residential building activity, albeit with a shift from detached housing. For example, higher interest rates and rising house prices are fuelling investment in multi-unit apartment and townhouse construction (Kelly, 2023a).

The construction environment is high-risk and is characterised by factors such as noise, dust, wastewater and mud (You & Feng, 2020). Construction involves labour-intensive processes (Karmakar & Delhi, 2021), using a combination of heavy manual labour and large-scale equipment. Building materials are constantly transferred during construction, adding to the complexities of the overall process (You & Feng, 2020). The sector also faces challenges due to its discontinuous processes, highly discrete nature and non-linear workflows, whereby different tasks are often delegated to subcontractors (You & Feng, 2020). The need for multiple participants situated in different locations to collaborate across changing environments can lead to spatial-temporal conflicts and scheduling issues (Qureshi et al., 2020; You & Feng, 2020) resulting in low productivity in project delivery (Turner et al., 2021; You & Feng, 2020), including delays, unforeseen costs and poor work quality (Maskuriy et al., 2019). Further, construction projects are becoming increasingly complex and complicated (Maskuriy et al., 2019), and subjected to increasing regulatory requirements, such as occupational health and safety, which explains the slow industrial evolution of the sector (You & Feng, 2020). In addition to the required interactions between multiple stakeholders, diverse climatic and geological conditions contribute to this complexity and uncertainty (Karmakar & Delhi, 2021; You & Feng, 2020).

Because construction remains one of the largest producers of CO_2 and consumer of energy and resources (Setaki & van Timmeren, 2022), the industry faces environmental scrutiny. Notably, among the four main phases of a building's lifecycle (design, construction, maintenance and demolition), the *construction and demolition* phases emerge as the most wasteful of physical resources (Setaki & van Timmeren, 2022). This is a significant cause for concern within the industry (Karmakar & Delhi, 2021). C&D waste increased by 25% from 20.2 Mt in 2016–17 to 25.2 Mt or (around 980 kg per capita) in 2020-21 in Australia, as shown in Figure 2 (Pickin et al., 2022). The waste includes many heavy waste types, such as concrete, brick and rubble. Most C&D waste is recovered from large development projects but less so from smaller projects and mixed material loads are often directed to landfills. These projects often also generate contaminated soil, which must be treated according to hazardous waste regulations, particularly where there are high rates of urban development, e.g., Victoria, New South Wales and South Australia.

While C&D waste is a key issue, it is important to note that the resource recovery rate for C&D waste is high, e.g., 80% in 2020-21. C&D waste and metal waste are the only streams that have achieved Target 3 of the **National Waste Policy**: an 80% average resource recovery rate from all waste streams following the waste hierarchy by 2030 (Australian Government, 2019). For example, there are markets for recycled concrete aggregate, which can be used as aggregate or hardstand areas and road bases. Recycled concrete aggregate will consolidate and form a harder and more stable hardstand than virgin aggregate. In addition, bricks, asphalt and other materials are recycled.

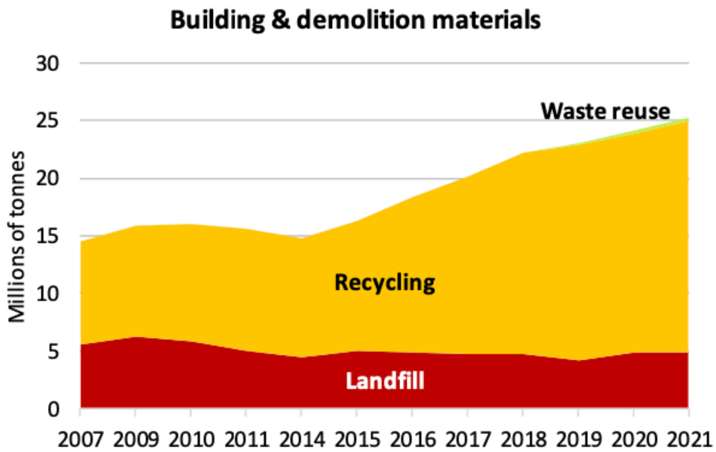


Figure 2. Generation and management of key waste materials, 2006-07 to 2020-21
Source: Pickin et al. (2022)

Figure 3 shows the material flow analysis of housing materials according to a recent CSIRO report (Miatto et al., 2024). A breakdown of the composition of 251 Mt of housing materials showed that the majority were non-metallics, followed by metal ores and then fossil fuels and biomass.

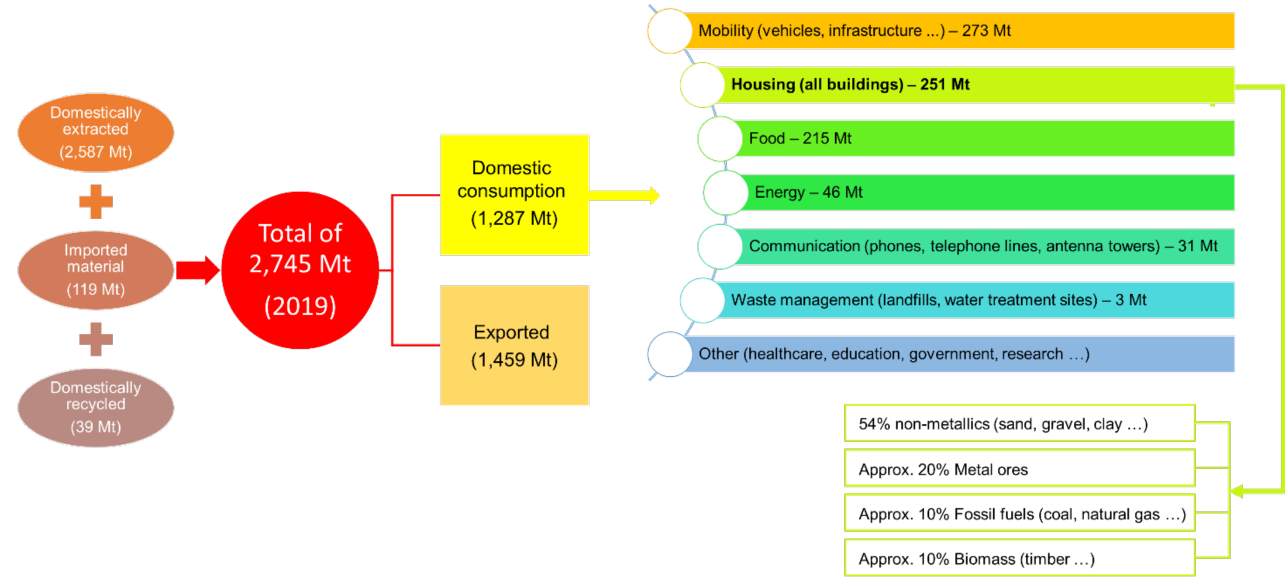


Figure 3. Material flow analysis of housing materials
Source: Own elaboration based on Miatto et al. (2024)

Recognising the imperative for change, traditional construction methods must evolve to meet the new demands of society to achieve a sustainable built environment (Chen et al., 2022). There is potential for developing new solutions and building components that minimise virgin material consumption and waste and offer significant positive environmental impacts. Consumption comes at a cost to the environment, from the energy and resources required to extract raw materials that pervade production to the enormous consequences of disposal. Therefore, addressing these challenges requires a holistic and transformative approach, integrating innovative technologies and sustainable practices throughout the construction lifecycle. The implementation of CE practices shows potential and serves as a pivotal strategy in facilitating a transition towards sustainable construction practices (Ngowi et al., 2020).

Our methods

This project involved a multidisciplinary research team and close collaboration with industry partners, supported by the Building 4.0 CRC. To gather comprehensive insights, the researchers completed a literature and market review to obtain a comprehensive overview of the circular landscape. They adopted a suite of research methods, including interviews, co-design planning workshops, case studies, observations and site visits (see Figure 4). The research was approved by the QUT Human Research Ethics Committee (approval number 7357). In addition, the researchers attended conferences, events, seminars and workshops to engage with industry and policy stakeholders and enrich their understanding of CE practices in Australia's building industry. This diverse approach resulted in a thorough assessment of the CE and its potential applications within the industry. Given the complex socio-political and economic factors at play and the potentially competing needs of key stakeholders, this scoping study will form a foundation for planning the necessary steps and actions to enable the transition to a CE.

Figure 4. Our methods
Source: Own elaboration

Workshops

To inform this research, ten co-design workshops were held with 80 participants between November 2023 and February 2024—including two in-person exploratory pilot workshops and eight online audio-recorded workshops (see Figure 5 and Table 1 for details). The workshops aimed to identify existing and potential circular initiatives in Australia and they provided an opportunity to eliminate siloed practices by bringing together key stakeholders from different construction areas. Accordingly, the workshop participants comprised a cross-section of government, industry and academics who are responsible for completing the project, work in construction, property or affiliated businesses and are leaders within the property and construction section. The participants informed researchers about what forces and drivers are being implementing or what they perceive can lead to significant circular change. These stakeholders included salient members of peak industry groups, investors, insurers, architects, designers, engineers, planners, developers, manufacturers, suppliers, waste management and logistics managers, regulators and policymakers from local, national and federal levels of government. Co-design is an effective method to collect data and generate ideas (Boone et al., 2023) and it is increasingly used to develop interventions to achieve results beyond scientific findings (Benson et al., 2021). As a result, the workshops allowed an in-depth exploration of the CE transition and encouraged participants to generate creative and novel ideas (National Social Marketing Centre, n.d.).

The workshops discussed design, technology, life cycle sustainability assessment, materials, supply chains and building processes, including education and training, certification and reporting practices, investment, insurance and policy and legislation governing the building and property sectors. In addition to the opportunities, the workshops aimed to uncover potential barriers and how to overcome them, as well as incentives that will help drive the transition to a CE.

Co-design workshops & interviews

Building Materials
BlueScope
Sumitomo Forestry
Hyne Timber
Holcim
VENTORA Glass

Developer
Stockland
Lendlease
Aurecon

Builder / Construction
Fleetwood Australia
Master Builders Victoria
A.G.Coombs
Skookom Building & Design
XFrame

Energy Supply
Stanwell

Architects, Engineers and Designers
Populous
Skidmore, Owings & Merrill (SOM)
GHD Design
Dsquared
Northern Edge Studio
Light House Architecture & Science
Cumulus Studio
BAR Studio

Demolition / Deconstruction
NTEX

Waste Management
Wanless
Additional waste management company
Alex Fraser

Research & Development / Education
holmesglen
QUT
Monash University
The University of Melbourne
CSIRO
RMIT

Peak Industry Bodies
VBA Victorian Building Authority
Australian Steel Institute (ASI)
Australian Sustainable Built Environment Council (ASBEC)
Waste Recycling Industry Association (NT) [WRINT]
Materials & Embodied Carbon Leaders' Alliance (MECLA)
Good Environmental Choice Australia (GECA)
Container Exchange
Adelaide Sustainable Building Network (ASBN)
Green Building Council of Australia (GBCA)
Australian Circular Economy Hub (ACE Hub)

Government
Victoria, Queensland, Northern Territory, Tasmania, Logan City, South Australia

Certifier / Insurance
Green Building Council of Australia (GBCA)

Users / Owners
Green Industries South Australia (GISA)
Heritage Lanes (by Mirvac)

Figure 5. Summary of workshop and interview participants, project partners' logos are depicted
Source: Own elaboration

The co-design workshops addressed the following research questions:

1. *How are you promoting circularity in your city/state/nationally?*
2. *What roadblocks or challenges do you face?*
3. *What information are you storing in BIM, digital twin systems or other technology that would enable people in the future to use these data?*
4. *How do you map the construction supply chain?*
5. *What is the role of policy and legislation to build better?*

6. *What are push-pull factors in construction accreditation and training to develop skills and knowledge for circular building?*
7. *What incentives should be put in place by investors/insurers?*

A priori coding, a form of deductive coding (Blair, 2015), was carried out using the same categories in the market and literature review to interpret the results in qualitative data analysis software. Preliminary findings were grouped into themes and evaluated to understand the evidence and to find gaps and areas for further exploration.

In addition to the ten co-design workshops, the research team has delivered three other workshops to the industry partners and Building 4.0 CRC, including a review meeting, a preliminary findings meeting and a final workshop.

Table 1. Summary of co-design workshops
Source: Own elaboration

#	State and city	Date
1	Brisbane (Pilot project)	6 October 2023
2	Melbourne (Pilot workshop)	7 October 2023
3	Melbourne	9 October 2023
4	Sydney	29 November 2023
5	Brisbane	30 November 2023
6	Darwin	12 December 2023
7	Adelaide	13 December 2023
8	Canberra	14 December 2023
9	Hobart	14 December 2023
10	Perth	21 February 2024
+1	Review meeting	27 February 2024
+2	Preliminary findings meeting	15 May 2024
+3	Final workshop	29 August 2024

Interviews

To inform this research, sixteen in-depth and semi-structured interviews were held between March and July 2024. The interviewees included key informants from various areas of construction, including education, peak industry bodies, architecture, design, technology, manufacturing and policy, among others, to collect deeper insights and write case studies on projects to evaluate how success is achieved (Table 2). The interviews allowed for a better understanding of viable business models and captured best practices as ideas for replication in creating a national strategic action plan. The research team prepared a general set of questions for each type of business and stakeholder and the semi-structured nature of the interviews allowed the researchers flexibility at the time of the interview to further investigate certain areas.

Table 2. Summary of interviews
Source: Own elaboration

#	Company	Type
1	Australian Circular Economy Hub	Peak industry body
2	Green Building Council of Australia (GBCA)	Peak industry body
3	RMIT	Education
4	VENTORA Glass	Supplier
5	Holcim	Manufacturer / supplier
6	XFrame	Technology / design / installation
7	Populous	Design and architecture
8	Wanless	Waste and recycling
9	Waste management company	Waste and recycling
10	NSW Government	Government
11	Engineering Design & Certifications	Certification
12	Alex Fraser	Recycling services
13	Green Industries SA (GISA)	Government
14	Architect	Design and architecture
15	Sumitomo Forestry Australia	Global construction and real estate
16	Light House Architecture & Science	Integrated design and science projects

Site visits

As part of this research, four site visits were conducted between March and July 2024 across multiple construction sites, existing facilities, refurbished and deconstructed facilities, waste management facilities and design studios (Table 3). These visits aimed to observe the practical application of CE principles in real-world settings. The research team documented operational processes, material flows, design principles and sustainability practices. These site visits provided firsthand insights into the successes encountered by industry professionals, contributing valuable data to developing case studies and informing recommendations for best practices in the sector.

Table 3. Summary of site visits
Source: Own elaboration

#	Site name
1	Wanless Recycling Centre in Western Sydney
2	47 Easey Street, Collingwood
3	CommBank Stadium, Parramatta
4	Heritage Lanes, Brisbane

Conferences and webinars

To address the research objectives, the researchers attended or participated in various activities, including conferences, webinars, events and podcasts (Table 4). These events were instrumental in gaining insights from industry experts and thought leaders. By participating in these events, the researchers could network, exchange ideas, stay current with the latest trends and innovations, identify emerging challenges and opportunities and enrich the study's depth and breadth. This information was added to the pool of evidence and subjected to a higher level of analysis to ensure the credibility and quality of the findings and reveal best practices as trajectories for *Building the Future through the Circular Economy*.

Table 4. Summary of events
Source: Own elaboration

#	Event name
1	Circularity Conference 2023
2	Circular Economy Research Network conference (CERN-Apac) 2023
3	PAIR Distinguished Lecture ‘Digital Twinning the Built Environment’
4	Discover the Future of Sustainable Building: Victorian 7-Star Transition and EE-04 CPD Event
5	Sydney Build Expo 2024
6	NABERS + CBD Conference
7	iX Summit Sydney
9	Rubbish on the Shore, Northeast Arnhem Land
9	Garma Festival, Northeast Arnhem Land
10	Think.Future podcast – build a better world
11	Guest lecture at the University of Queensland about Circular Economy in the Building Sector
12	Populous Sustainability Week presentation

PROJECT FINDINGS AND OUTCOMES

Context

The Australian building industry operates within a dynamic context, constantly evolving with new rules and regulations. These regulations are designed to ensure safety, sustainability and compliance with industry standards, requiring continuous adaptation and awareness from all stakeholders.

Government and regulatory environment

In Australia, the development of policies regarding CE in general falls under the ***Department of Climate Change, Energy, the Environment and Water*** **(DCCEEW)**. While there is no established CE directive, the DCCEEW has communicated its intention to foster progress and the CE transition. All of Australia's environment ministers have agreed to work with the private sector to achieve a CE by 2030 (Department of Climate Change, Energy, the Environment and Water [DCCEEW], 2024a).

A ***Circular Economy Ministerial Advisory Group*** was established in February 2023 to advise the Australian Government on its transition to the CE. Individual members were selected based on their expertise and ability to deliver evidence-based research and input from a wide range of stakeholders. This includes assessing the opportunities versus barriers in progressing a CE, best practices to be considered for adoption or expansion, key research and development needs and effective methods to communicate and measure what is being achieved (DCCEEW, 2024a). The Built Environment is one of the focus areas of the 15-member Advisory Group.

In April 2024, an interim report was issued to demonstrate the Advisory Group's early commitments (DCCEEW, 2024a). The report contained a section on the construction sector to show the urgency of making commitments within the industry, outlining the *'First steps for building sector actors to adopt circular principles'*. A final report will be delivered at the end of 2024 to support domestic manufacturing capabilities and jobs. The Advisory Group has proposed to:

- set up a Productivity Commission Inquiry to investigate how resource efficiency can support economic growth,
- develop the national CE framework with the power to establish circular standards for products and materials,
- introduce a 'recycled content first' policy to stimulate a recycled market, and
- determine and embed sector-based CE targets and principles in key climate policies.

In addition, the Australian Government released an **Environmentally Sustainable Procurement Policy** (ESP Policy). Construction services at or above $7.5 million was one of the procurement categories that was adopted and became effective on 1 July 2024. This policy shows potential to drive a circular marketplace along the value chain because the government not only plays an instrumental role in rolling out such a program but is also Australia's largest procurer of goods (DCCEEW, 2024b). Significantly, it helps to provide a measure of relief and confidence at a time when building or rebuilding is needed to resolve acute housing shortages and there is high market volatility due to increased material costs, labour shortages and industry insolvencies (Sheth-Patel, 2024), as displayed in Figure 6.

The ESP Policy was written with the intent to apply *climate* (focusing on greenhouse gas [GHG] emissions, energy efficiency and low embodied emissions), *environmental* (focusing on water efficiency, renewable inputs, safe use and disposal of chemicals and waste minimisation) and *circularity* (focusing on keeping resources in use for longer and sustainable production and consumption) principles. Specifically, the circularity principles underline strategies focusing on less material use in buildings and fit-outs and they promote the use of durable, repairable, reusable, or recyclable goods, as well as leasing and renting services (DCCEEW, 2024c).

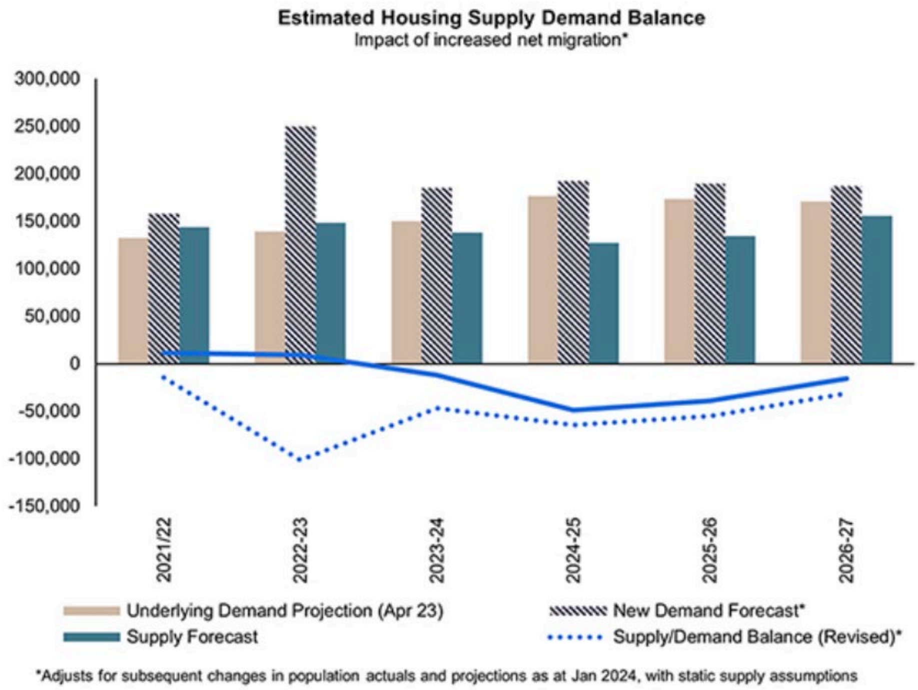


Figure 6. Australian demand and supply housing projections
Source: Sheth-Patel (2024)

The **ReMade in Australia** program is an initiative that is linked to the ESP Policy. It is a certification trademark that aims to reward manufacturers for producing goods with recycled content. In meeting the sustainability outcomes of the policy, businesses bidding for government construction services can apply the funding to reduce or repurpose waste or replace single-use materials with recycled ones (DCCEEW, 2024d). Thus, it is an incentive to meet or exceed the National Waste Target 3 at 80% average resource recovery from all waste streams by 2030 (Australian Government, 2019).

Moreover, the federal government proposed metrics to help suppliers understand how to report during the transition in phase 1 of the ESP Policy and Procurement Framework (DCCEEW, 2024c). Therefore, it provides a measurement and reporting framework to facilitate tracking environmental outcomes using verification measures.

Many states and local government authorities are preparing their approaches to support markets and drive innovation in recycling and remanufacturing across all waste and resource streams, focusing on construction. New South Wales (NSW) has released a policy to create a new market for recycled materials across Australia's construction sector, outlined in the state's *Decarbonising Infrastructure Delivery Roadmap* (Infrastructure NSW, 2024). It is part of a draft *'Protection of the Environment Policy'* for sustainable construction. Queensland (QLD) has prepared a *Waste Management and Resource Recovery Strategy* (Queensland Government, 2024) to build economic opportunity and reduce the impact of waste on the environment. South Australia (SA) has a long history of acting through its diverse programs to use less natural and raw materials, retain the use of products and design out waste and pollution. Green Industries SA (2020) enables these initiatives and they also support the Waste Strategy 2020-2025. Victoria (VIC) recently released a plan titled *Recycling Victoria: A new economy to propel recycling and reuse* (Victoria State Government, 2024). Western Australia (WA) has established a Waste Authority business and action plan for 2024-2025 (Waste Authority WA, 2024). Northern Territory (NT) has released a *Circular Economy Strategy 2022-2027* (Northern Territory Government, 2022) to identify material recovery and reuse opportunities in the built environment. In addition, ACT passed its own *Circular Economy Strategy and Action Plan 2023-2030* (ACT Government, 2023) to work towards a circular city by setting a vision, strategic objectives and focus areas. Lastly, Tasmania has developed a framework, the *Tasmanian Waste and Resource Recovery Strategy 2023-2026* (Tasmanian Waste and Resource Recovery Board, 2023), to position the state for a CE, with approaches for various sectors and policy areas. Many of these schemes will reinvest funds from landfill levies to finance waste initiatives. Overall, these concerted efforts reflect a growing movement for government action.

Climate change targets

The Paris Climate Agreement's target for the global energy sector alone to reach net zero by 2050 (Rogelj et al., 2018) fundamentally conflicts with continuing the traditional building culture. Current approaches fail to consider that the use life of building materials is often longer than the operational life of the space or building they are used for (United Nations, 2021). While it is predicted that by 2050, the building floor area in the world will double, the long life of buildings means most of the consumption will be due to inefficiency in existing buildings. In the European Union (EU), today's buildings will make up approximately 70% of the building stock in 2050 (International Resource Panel, 2020). Of these, about 35% are over 50 years old and almost 75% of the building stock is energy inefficient. In Australia, the existing building stock equates to approximately 98% and only 2% is new. The potential of working with and retrofitting existing building stock is critical to reducing the environmental impacts of buildings and mitigating climate change.

Climate change, coupled with the extreme weather conditions that Australia experiences, imposes greater risks of floods, fires and droughts. Worsening global patterns indicate an increasing likelihood of these threats. Thus, it is essential for properties to incorporate resilient features to protect against the impacts of severe weather (Simmons, 2021). Although technologies and materials are now becoming more robust, these innovations do not cover many existing and mainstream buildings, leaving Australians exposed to natural disaster shocks. For instance, flooding in Lismore in 2022, NSW, displaced many people and caused a loss of property values. Numerous residents found premiums unaffordable or were unable to source insurance in areas prone to weather-related disasters (Chenery, 2023). The Australian Government introduced mandatory climate-related financial disclosures to assess and manage systemic risks by large corporations and asset owners to mitigate the effects of climate change in the national transition to net zero (Treasury, 2024).

Nevertheless, all building typologies should be designed to protect homeowners, renters and businesses. The Intergovernmental Panel on Climate Change (IPCC) stipulated that governments should make urban planning a front-line approach to adapt to climate change (Rogelj et al., 2018). They recommended that land-use planning be updated to consider nature, involve communities and integrate tools to foresee risks and uncertainties. Scenario planning, water-sensitive design, carbon assessments and monitoring the latest climate science in making land use decisions are perceived as necessary responses (Norman, 2022).

The IPCC projects that 3.3 to 3.6 billion people globally live in highly vulnerable areas. Australia suffers from natural catastrophes that impact the natural and built environment, such as the Black Summer bushfires of 2019-20. Therefore, impact hot spots should be identified and planning decisions should be proactive, beginning with being prudent about where and how people can build and taking measures to promote carbon-neutral development and climate adaptation to increase jobs and stimulate economic growth (Simmons, 2021).

The federal government is analysing and updating its commitments to climate action (Climate Change Authority, 2024), including a Nationally Determined Contribution to take responsibility for environmental impacts while promoting equitable and sustainable development. In 2019, Commonwealth, state and territory energy ministers agreed to develop a national plan that aims to achieve zero energy and carbon-ready commercial and residential buildings—the **Trajectory for Low Energy Buildings**. The Trajectory should lead to lower energy bills, contribute to energy security and affordability, reduce carbon emissions, improve people's comfort and health, reduce wastage for the wider economy and assist in lowering peak demand.

On the global scene, the World Green Building Council (2024a) has issued a vision for new buildings, infrastructure and renovations to have at least 40% less embodied carbon by 2030 with significant upfront carbon reduction and for all new buildings to be net zero carbon in their operation. In addition, the Council wants all buildings to reach net zero embodied and operational carbon by 2050.

Australian building codes

Australia's **National Construction Code (NCC)** is the primary set of technical design and construction provisions. It is governed by the **Australian Building Codes Board (ABCB)** on behalf of the Australian Government and each state and territory (Australian Building Codes Board [ABCB], 2022). The NCC establishes minimum required levels for the safety, health, amenity, accessibility and sustainability of buildings and is based on performance.

The NCC is applied to new buildings, but it is also applicable to major renovations. Thus, when works require building consent approval by authorities, they are subject to the regulations and provisions in the NCC (ABCB, 2022). Each type of building or structure is classified according to the purpose for which it is designed, constructed or adapted. It is recommended that all structural designs be prepared by experienced designers or builders and they may require preparation or review by a qualified engineer. All masonry construction must also comply with the NCC and Australian Standards.

The NCC groups locations around Australia into eight climate zones. These zones are depicted in Figure 7 and indicate what are deemed to satisfy (DtS) provisions for heating and cooling requirements in each location that shares a similar climate (ABCB, 2022).

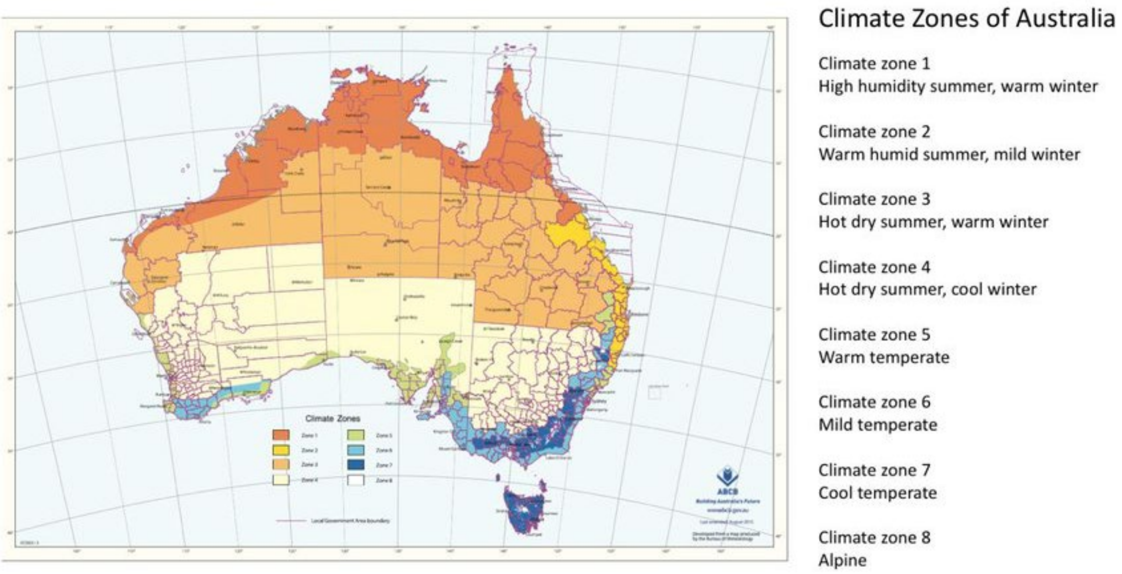


Figure 7. Australian climate zones
Source: Australian Building Codes Board (2022), CC BY 4.0

Following the climate zones, different energy efficiency standards are prescribed for different classes of buildings across these environments. The minimum recommended energy efficiency standard for new homes is 6 stars, representing environmentally sustainable building practices and helping to lower household energy use, particularly during peak demand periods. Most states and territories have been transitioning to the updated NCC 2022 Code of a higher 7-star level in conformance with the **Nationwide House Energy Rating Scheme's (NatHERS)** approved software. Tips and guidance are provided by the National Construction Code [NCC] (2022).

The **Building Sustainability Index (BASIX)** is another tool to reduce the environmental impact of new residential buildings in NSW. The highly regarded **National Australian Built Environment Rating System (NABERS)** Commercial Building Disclosure (CBD) program is also poised for extension because it identifies cost savings and future improvements and provides a transparent report for stakeholders (World Green Building Council, 2024b).

Literature review

The literature review identifies key trends, challenges and opportunities that shape current CE practices. It establishes a foundation for the empirical research conducted in this study, ensuring that our findings are grounded in and contribute to the ongoing discourse in these fields.

The literature review includes the following sections: circular design strategies, lifecycle assessment and lifecycle sustainability assessment, Industry 4.0 technologies and materials in construction.

Circular economy

The **Ellen MacArthur Foundation** proposed the following definition:

> **Circular economy**: '*An industrial system that is restorative or regenerative by intention and design. It replaces the end-of-life concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse and return to the biosphere, and aims for the elimination of waste through the superior design of materials, products, system and business models.'* (Ellen MacArthur Foundation, 2013).

In addition, in 2024, the **International Organization for Standardization (ISO)** published a new family of standards (ISO 59000) that provide organisations with tools and guidance to implement, measure and enhance circular practices. The ISO's CE standards mark an important shift in facilitating the CE transition, similar to the ISO's use of the Life Cycle Assessment (LCA) standards in the 1990s. Thus, the ISO provides an important framework for businesses developing their new circular approaches. Specifically, the ISO introduced ISO 59004 (vocabulary, principles and guidance for implementation), ISO 59010 (guidance on the transition of business models and value networks) and ISO 59020 (measuring and assessing circular performance). The ISO reported key definitions in relation to the CE and this transition, as follows:

- ✓ **Circular economy**: *'economic system that uses a systemic approach to maintain a circular flow of resources, by recovering, retaining or adding to their value, while contributing to sustainable development'* (ISO, 2024, p.1).
- ✓ **Circularity**: *'degree of alignment with the principles for a circular economy'* (ISO, 2024, p.3).
- ✓ **Circularity aspect:** *'element of an organization's (activities or solutions that interacts with the circular economy. Example: Durability, recyclability, reusability, repairability, recoverability.'* (ISO, 2024, p.13).
- ✓ **Circularity assessment:** *'evaluation and interpretation of results and impacts from a circularity measurement'* (ISO, 2024, p.13).
- ✓ **Circularity impact:** *'change to economic, social and environmental systems, whether adverse or beneficial, including possible consequences, wholly or partially resulting from an organization's circularity aspects'* (ISO, 2024, p.13).
- ✓ **Circularity indicator:** *'metric used to measure one or more circularity aspects'* (ISO, 2024, p.13).
- ✓ **Circularity measurement:** *'process to help determine the circularity performance through collection, calculation or compilation of data or information'* (ISO, 2024, p.13).
- ✓ **Circularity performance:** *'degree to which a set of circularity aspects align with the objectives and principles for a circular economy'* (ISO, 2024, p.13).
- ✓ **Closed loop system**: *'system by which products or resources are used and then recovered and turned into new products or recovered resources, without losing their inherent properties'* (ISO, 2024, p.11).

- ✓ **End of life**: *'<product> point in time when a product is taken out of use and its resources are either recovered for processing or it is disposed of'* (ISO, 2024, p.11).
- ✓ **End of use**: *'point in time at which a product or resource is transferred by the holder to some other holder'* (ISO, 2024, p.11).
- ✓ **Energy recovery**: *'generation of useful energy through direct and controlled transformation of recovered resources'* (ISO, 2024, p.7).
- ✓ **Life cycle**: *'consecutive and interlinked stages in the life of a solution'* (ISO, 2024, p.5).
- ✓ **Life cycle perspective and life cycle thinking:** *'consideration of the circularity aspects relevant to a solution during its life cycle which includes consideration of the relevant environmental, social and economic impacts'* (ISO, 2024, p.5).
- ✓ **Linear economy**: *'economic system where resources typically follow the pattern of extraction, production, use and disposal'* (ISO, 2024, p.10).
- ✓ **Non-renewable resource**: *'resource that exists in a finite or limited amount that cannot be naturally replenished within a foreseeable time frame'* (ISO, 2024, p.7).
- ✓ **Recoverable resource**: *'resource that can be recovered and used again after it has already been processed or used'* (ISO, 2024, p.6).
- ✓ **Recovered resource or secondary resource**: *'resource that is obtained from one that has already been processed or used'* (ISO, 2024, p.6).
- ✓ **Renewable resource**: *'resource that can be naturally or artificially grown or replenished within a foreseeable time frame by processes found in nature'* (ISO, 2024, p.7).
- ✓ **Reverse logistics**: '*process of managing, collecting and moving products from their current location after the end of use for the purpose of recovering or retaining value through proper handling*' (ISO, 2024, p.7).
- ✓ **Sustainable development**, following the Brundtland Report: *'development that meets the environmental, social and economic needs of the present without compromising the ability of future generations to meet their own needs'*. (ISO, 2024, p.11).
- ✓ **Value chain**: *'set of organizations that provide a solution that results in value for them'* (ISO, 2024, p.9).
- ✓ **Value network**: *'network of interlinked value chains and interested parties'* (ISO, 2024, p.9).
- ✓ **Virgin resource or primary resource**: *'natural resource or energy that is used as a resource for the first time as input in a process or for creating a solution'* (ISO, 2024, p.5).
- ✓ **Waste**: *'resource that is no longer considered to be an asset as it, at the time, provides insufficient value to the holder'* (ISO, 2024, p.6).

One way to conceptualise CE activities is through the Ellen MacArthur Foundation (2013)' butterfly diagram (Figure 8). This diagram represents the continuous flow of materials along two main cycles—the technical and the biological. In the technical cycle, the products, components and materials are circulated through reuse, repair, remanufacture, or recycling. These strategies aim to minimise systematic leakage and negative externalities. The biological cycle focuses on biodegradable materials and returning nutrients to the Earth to regenerate nature. These materials are renewable by nature and are cycled in biological cycles or can be consumed, such as food (Ellen MacArthur Foundation, 2019).

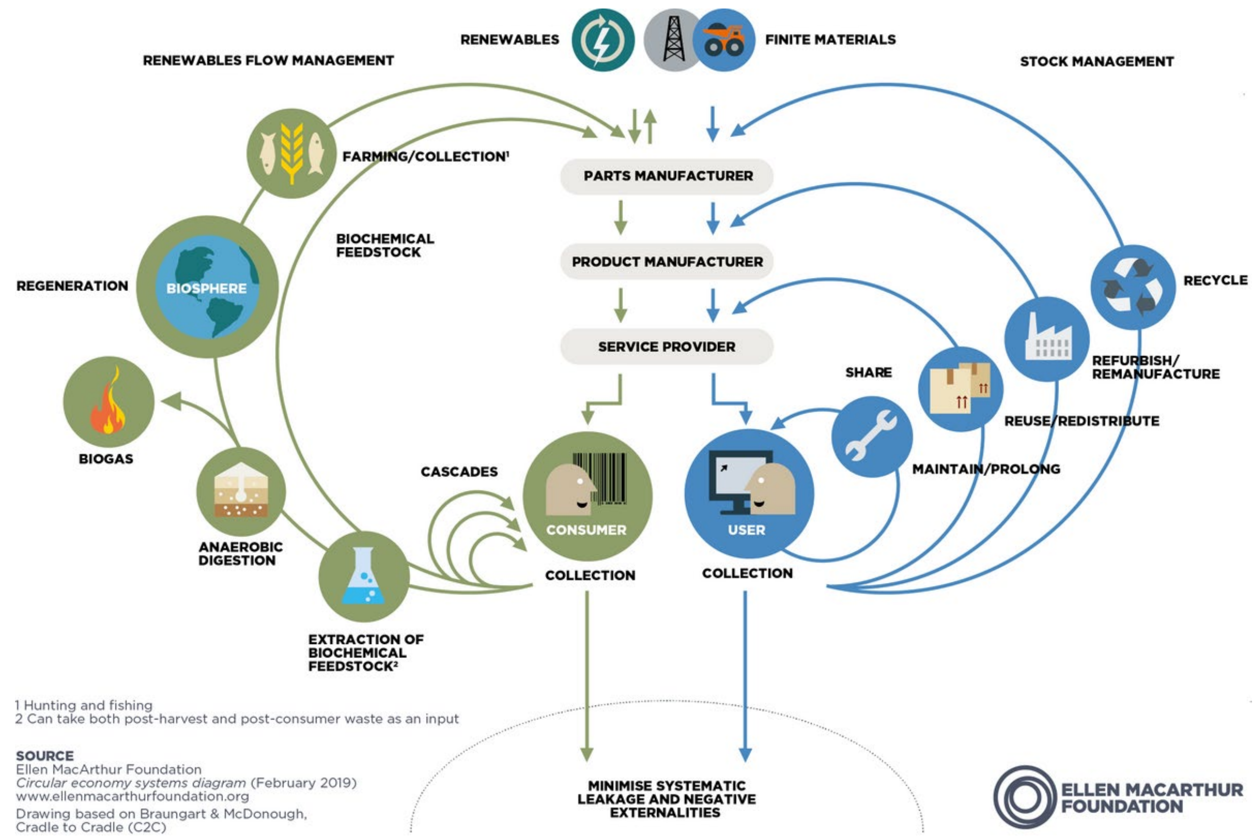


Figure 8. The butterfly diagram of the Ellen MacArthur Foundation
Source: Ellen MacArthur Foundation (2019)

Another way to conceptualise CE strategies is by following and assessing the 10R levels of circularity, also known as the hierarchy of circularity strategies (Figure 9). It shows an order of priority and, by climbing up the circularity ladder, it is possible to prevent waste and create more potential value from existing products and materials (Cramer, 2017). Some of these concepts have also been included in and defined by the new ISO standard (ISO, 2024).

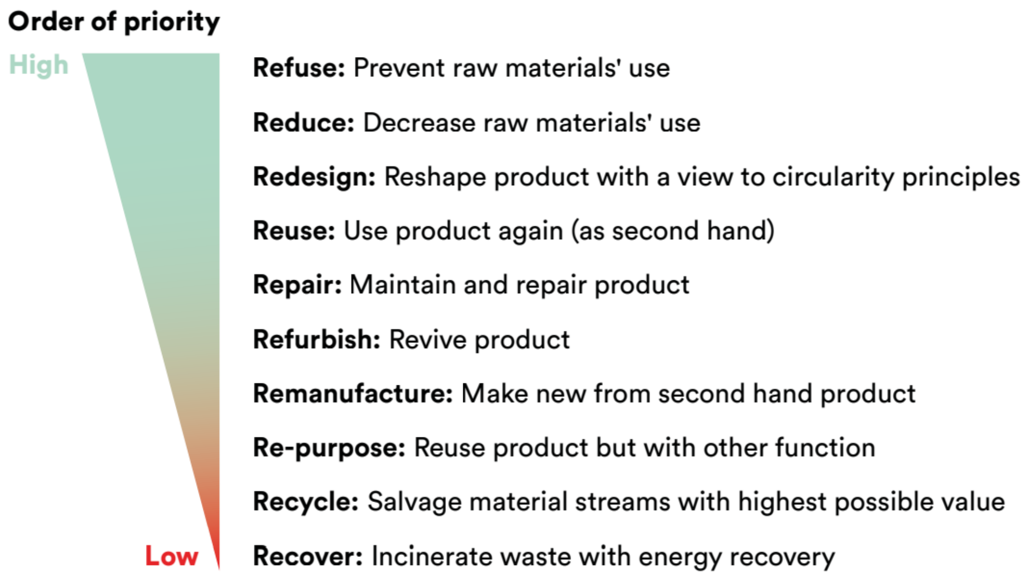


Figure 9. 10R levels of circularity
Source: Cramer (2017)
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Although the CE concept has gained worldwide attention (Pomponi & Moncaster, 2017), the 2024 circularity gap report published by the **Circle Economy Foundation** indicated that it is falling short of progress (Circle Economy Foundation, 2024). The majority of extracted materials entering the economy are still virgin materials and extraction is at record levels. Secondary materials use declined to 7.2% in 2023 from 9.1% in 2018 (Fraser et al., 2024), which underlines how important it is to translate principles into better practices, using innovation for successful systemic change. This is particularly relevant in the construction industry, driven by its aim to become more sustainable and, thus, it is important to understand how CE strategies and principles can be adopted in the construction sector.

The Ellen MacArthur Foundation defined three key principles for CE: 1) eliminate waste, 2) extend lifecycle and 3) regenerate nature (Ellen MacArthur Foundation, 2015). The CE model offers a chance to move towards more sustainable growth as resources, emissions and energy are minimised by slowing, closing and narrowing material and energy loops (Bocken et al., 2016) and by establishing a cyclical system in which products and materials are kept in use and waste is designed out (Ellen MacArthur Foundation, 2013). Similarly, the Circle Economy Foundation (2024) highlights that four flows of CE need to be considered based on the principles of using less, using longer, using again and making clean (Figure 10).

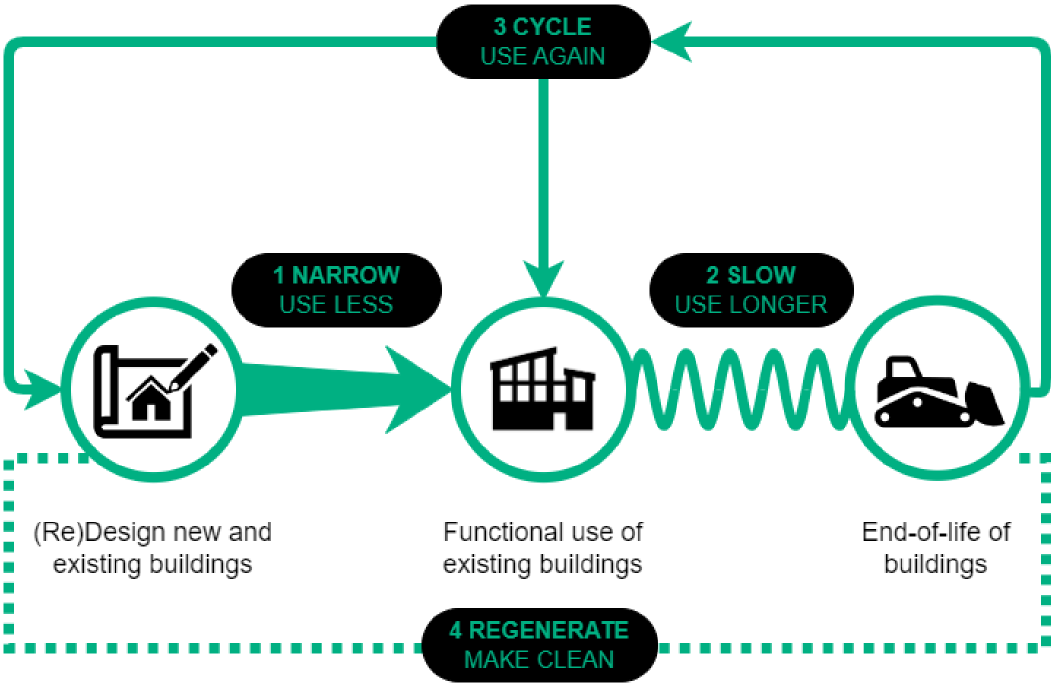


Figure 10. Reimagined representation of narrow, slow, cycle and regenerate
Source: Adapted from Circle Economy Foundation (2024)

The Circle Economy Foundation (2024) lists Australia among the Shift Countries, which are characterised by high levels of consumption and a high Human Development Index (HDI), but which contribute substantially to the overshooting of planetary boundaries. Consequently, they recommend that these countries should focus on four of twelve circular solutions: 1) Extending the lifetime of machinery, equipment and goods, 2) Buy what you need, 3) Make the most of what already exists, and 4) Prioritise circular materials and approaches.

Cramer (2022) identified four CE transition phases based on the implementation of national policies on CE, the percentage of recycled household waste, and attention to redesign and reuse of products. The four phases are predevelopment (no national policies on CE), startup (national policies on CE in development), acceleration (national policies on CE in place) and stabilisation (national policies on CE as 'the new normal'). Based on these criteria, Australia was placed in the **predevelopment phase** (Cramer, 2022). However, because the focus of the federal government has shifted to the development of national policies on CE in Australia, it has now entered the **early startup phase**.

Circular economy in construction

The construction industry, recognising the imperative of sustainability, is evolving to meet the demands for energy efficiency, waste reduction, quality building and intelligent indoor environments

(Chen et al., 2022). Circularity is promising in the context of construction and property because it can introduce new ways to address design, materials and building issues during heightened demand for housing and infrastructure (Maskuriy et al., 2019). Improvements must also continue to advance within commercial and industrial sites, especially to adapt to climate change.

Post-consumption, construction materials should be recovered as valuable resources for reuse, remanufacturing, or recycling in line with the most desired options of the waste hierarchy (Zhang et al., 2022) and circularity. This presents the possibility of achieving a CE and diminishing the carbon footprint of construction materials. However, a notable challenge lies in classifying diverse waste materials (Karmakar & Delhi, 2021). In Australia, the National Waste Policy 2018 defines C&D waste as *'waste produced by demolition and building activities, including road and rail construction and maintenance and excavation of land associated with construction activities'* (Australian Government, DCCEEW, 2019), although each jurisdiction has its own wording and practical applications of C&D waste. C&D materials include asphalt, bricks, concrete and pavers, ceramics, tiles and pottery, plasterboard and cement sheeting, soil, sand and rock. However, C&D activities also produce other types of waste, such as metals, organics, paper and cardboard, plastics and glass.

In addition, **urban mining** should be explored for circular construction, because it enables actors in design, planning and construction to shift their focus to the anthroposphere as a source of, rather than a destination for, processed goods. Material stocks in urban systems and anthropogenic resources could be reintegrated and used in new production cycles (Markopoulou & Taut, 2023). An alternative approach to sustainability involves substituting traditional construction materials with more environmentally friendly alternatives to reduce the overall impact (Elghaish et al., 2022). Another key point is reducing the use of virgin materials while achieving the same or better performance.

The adoption of a CE in the construction industry requires more practical solutions (Elghaish et al., 2022). For instance, Ngowi et al. (2020) emphasise the critical need for improvements in design, management, operations and decision-making of construction projects. For instance, refurbishment may be viable, although planning policy may support or hinder redevelopment. In London, UK, the government rejected the demolition and replacement of Marks & Spencer's Oxford Street store in favour of reusing the existing building, mainly due to environmental impacts. Despite motivation from the top down and bottom up to make improvements and support a CE, market pressures and legislative requirements make this process challenging (Skinner, 2023). Due diligence, meeting regulations to demonstrate compliance with warranty provisions, building and fire regulations, manufacturer requirements and evidence of maintenance and fire integrity are some criteria that make it easier to choose new installations. Repurposing products can also be inhibited by perceptions that used floors, for example, may not be as appealing or are not subject to warranty provisions. Testing and due diligence can facilitate the reuse of materials to support a CE and to ensure construction adheres to standards governed by the construction code.

London Skyline (Leonie Barner, 2024)

The transition to a CE is also complex because of the many **stakeholders** in the built environment industry. Stakeholders in the built environment comprise both public and private sector actors, as shown in Figure 11. From a broader societal perspective, everyone is an actor because we all use built environment assets to live and work. Therefore, circular solutions must be sought by actors working across the construction value chain. At the earliest stages of project inception, architects, designers and engineers will consider optimal methods to create a structure and prolong its use.

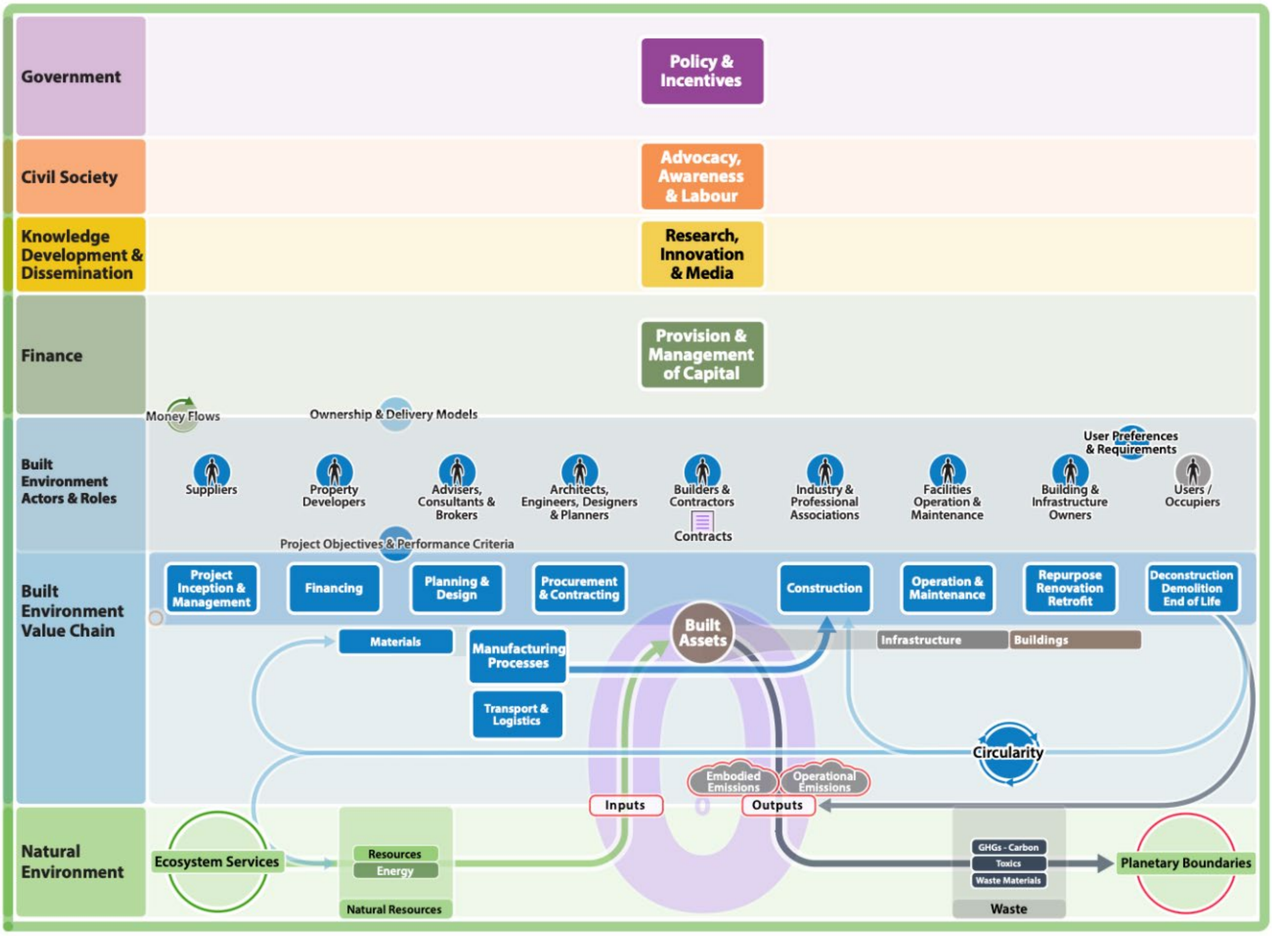


Figure 11. Built environment system map
Source: Nexial & UN Climate Champions Team (2021)

In addition to the great number of stakeholders, many different layers within a building are impacted by new methods addressing a CE. Brand (1995) wrote the seminal book on the different layers of buildings: *How Buildings Learn: What Happens After They're Built*. His premise was that buildings are adaptable and are meant to be refined by their occupants over time. Every building has a series of outer and inner layers, which he referred to as the '6S framework' that can be distinguished and designated with different life spans, as seen in Figure 12:

- **Site**—The site is the land, water and built environment on which something has been constructed. Roads and transport systems may also form part of the site.
- **Structure**—The structure comprises walls, columns, beams, bracing, flooring and the foundation.
- **Skin**—The skin is the envelope of a building, encapsulating cladding or weatherboarding, insulation, a cavity and joinery components.
- **Services**—All mechanical, electrical and plumbing systems must jointly function to operate a building.

- **Space plan**—The finishes affixed to the interior of a primary structure make up the space interior. Finishes include suspended ceilings, non-load bearing and service walls, raised floors, doorways and halls.
- **Stuff**—Objects detached or capable of being easily removed complete a building and may include furniture, supplies, cars, electronics and storage devices.

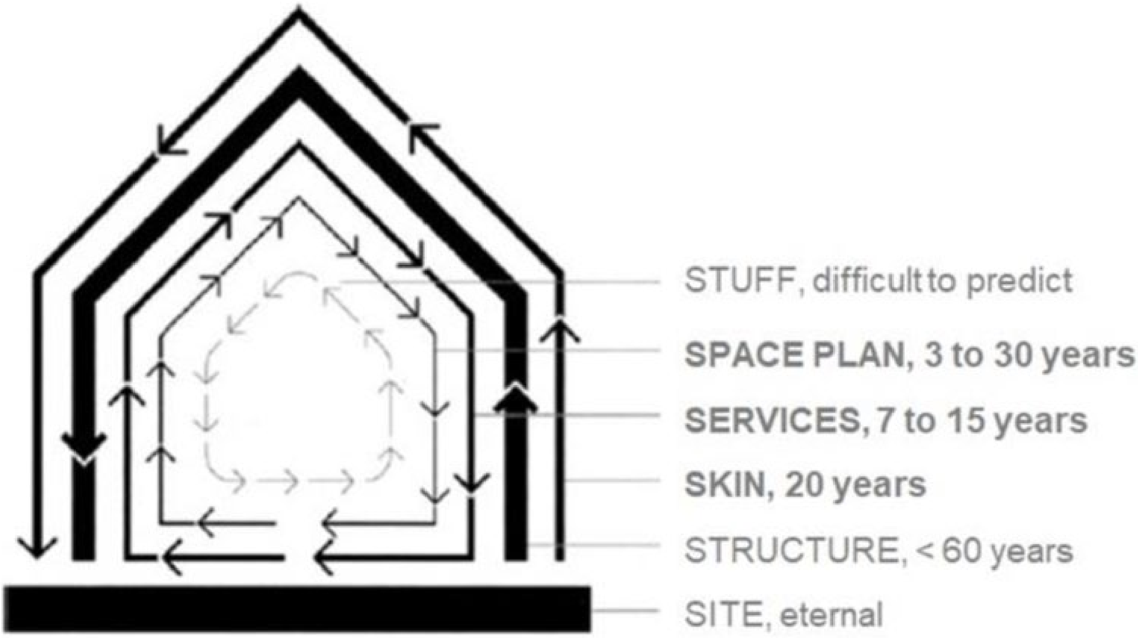


Figure 12. Buildings as layers
Source: Castro and Pasanen (2019)
CC BY 3.0

Whether a project already exists or is new, there are different options to ensure that all the layers—consisting of the site, skin, structure, services, space and stuff placed in a building—can achieve high environmental performance, comfort and convenience and are cost-effective for owners and tenants. Nearly 1,200 Australian architects have pledged to adopt practices that create a greater positive impact within our ecosystems (see Appendix 1).

Circular design strategies

Eco-design is defined as a systematic approach that considers environmental aspects in design and development to reduce adverse environmental impacts throughout the lifecycle of a product, according to ISO 14006:2020(en) (ISO, 2020). It may be achieved through environmental assessment and improvement (Vallet et al., 2013) of materials, energy, water and waste for new and existing structures, including modifying processes needed to deliver products. Common eco-design strategies to keep products and materials in longer use, to repurpose them or to prevent excess waste are presented in Table 5. These eco-design strategies are imperative and thus are proposed for application during the construction of new or redesigned buildings, as shown in Figure 13.

Table 5. Eco-design strategies
Source: Adapted from Allameh and Heidari (2020)

Design for Manufacturability (DfM): Enable pollution prevention during manufacturing Design for less or fewer different materials Design for safer materials and processes	**Design for Longevity (DfL):** Provide lifetime usage Improve flexibility, modularity and serviceability Design parts/products so they can be reused elsewhere
Design for Energy Efficiency (DfEE): Reduce embodied energy of building products Install renewable energy Aim for lower emissions with carbon sinks	**Design for Modularity (DfMo):** Construct prefabricated buildings that allow for upgrading, replacement and service Ensure portions of 2D panels, 3D modules or hybrid modular construction can be disassembled for extended life
Design for Dematerialisation (DfD): Use less raw material in selecting products with less mass Reduce packaging and eliminate unnecessary single-use items Modify manufacturing processes so by-products are reduced Use recycled materials	**Design for Disassembly (DfDi):** Select components that can be quickly and cost-effectively taken apart and re-used Model a structure for complete disassembly Engineer parts to be efficiently dismantled using simple tools
Design for Multifunctionality (DfMu): Use one product for different purposes Design in flexibility to enable changes with products to operate within larger systems and be interactive so multiple users can access and use different features	**Design for Logistics (DfL):** Use local materials wherever possible Minimise transportation for incoming or outgoing supplies to sites Organise for waste management companies to forward most of the waste to alternative users or reprocessors
Design for Recycling or Using Recycled Materials (DfR): Order items that contain recycled materials or have the capacity to be recycled in relatively close proximity Design for greater resource recovery by coding parts so they can be easily identified and source-separated in accessible recycling bins at the post-consumption stage	**Design for Healthy Environments (DfHM):** Specify safe, non-toxic materials Maximise landscaping with natural, endemic plants and green spaces that stimulate biodiversity and healthy, calm settings for people's enjoyment

Construction project performance is no longer judged solely on time, cost and quality. Pressure to lower carbon emissions is now causing shifts towards eco-friendly practices.

Ecological considerations can solve many problems, including mitigating pollution, conserving natural resources and preventing environmental degradation, and they can be achieved by integrating **passive design techniques** into a built form (Udomiaye et al., 2018). A passive building generally has continuous insulation, airtight windows, good natural light and ventilation and double or triple glazing to prevent heat loss. Overhangs or curtains offer shading and passive designs determine the best position to locate a building on a block of land to maximise energy efficiency for the building's operation. These measures can have a significant impact on reducing operational energy.

Alternatively, energy demand can be reduced through inputting active solar technologies around the exterior of a building. Planting trees and other vegetation outdoors are ways to block out sun and wind and advance health and wellbeing for inhabitants. Built environments, like humans, can metabolise nutrients and waste and, therefore, buildings should be designed to catch, store and filter water, purify air and process other nutrients (Ragheb et al., 2016). These techniques make a building more comfortable and healthier for the dwellers.

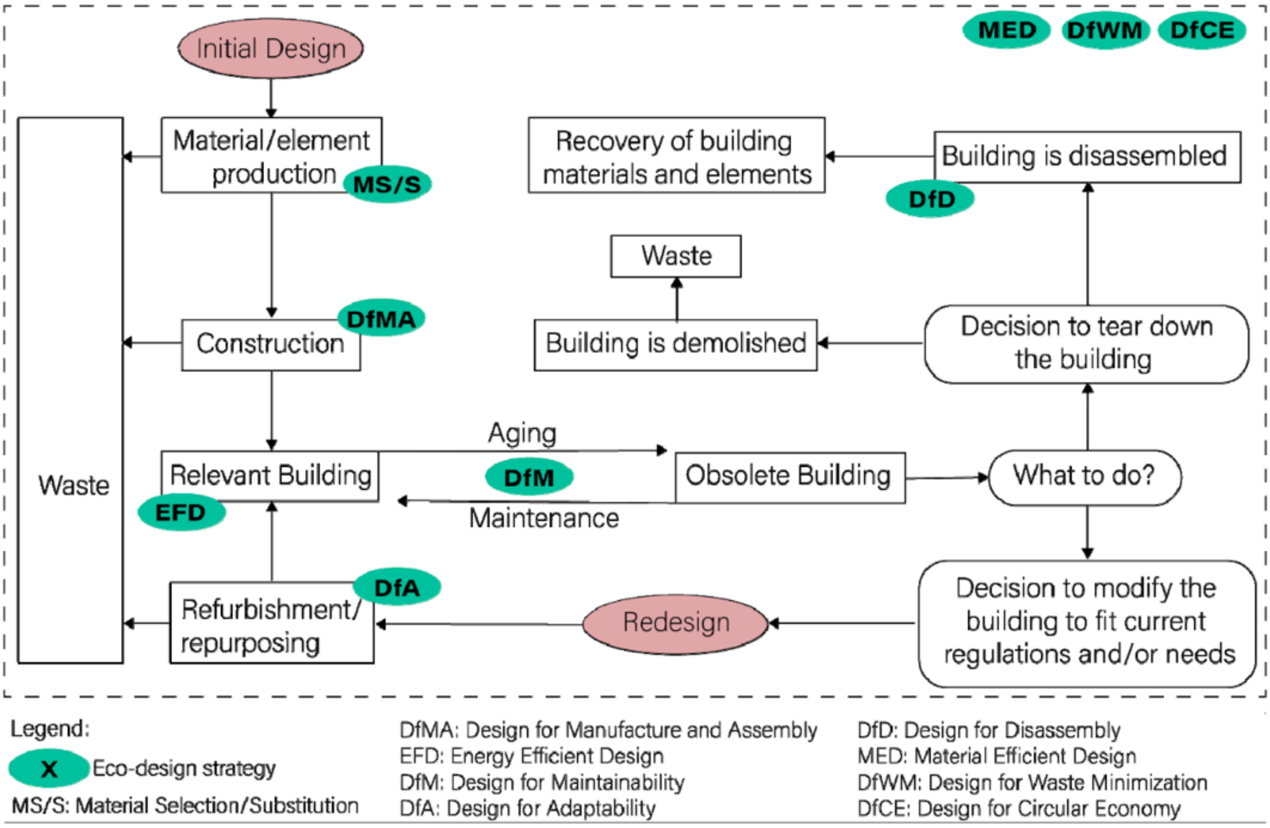


Figure 13. Eco-design strategies for constructing new and existing buildings
Source: From Ipsen et al. (2021)

Vernacular design is another way designers can increase and enhance thermal comfort and energy efficiency (El Azhary et al., 2021). This process reflects how architects orient low-rise houses and choose local or regional materials for building, such as clay bricks, which regulate extreme weather effects during summer and winter. This material suits the predominantly arid, sub-tropical continent of Australia. It can be found in the diverse styles that define Australia's early architecture, from the Victorian, federation and Art Deco periods (Margalit, 2019), and is found in newer architectural styles.

Traditional or modern high-rises in urban environments can also be designed using eco-friendly settings, fitting them with natural, green roofs to adapt to harsh city environments. Green roofs can lower energy costs and provide insulation. However, it is important to critically assess the active energy costs in pumping water to the vegetation and increase structural loads due to heavy water and soil high in the building.

There is a growing penchant for incorporating green roofs, walls, courtyards and parklands in urban projects. Green spaces are beneficial to counter the urban heat island effect (Irfeey et al., 2023), whereby heat becomes trapped and radiates (Udomiaye, et al., 2018), leading to dangerous consequences if cooling systems fail on extreme heat days (NSW Government, 2024).

Indoor and outdoor landscapes with parks, bushland and vertical green and community gardens with seating and other places encourage healthier lifestyles and public congregation. They can be vital to offset stress and support health and wellbeing (Ward Thompson et al., 2016). They also promote:

- lower heating and cooling requirements for a building
- lower and slower stormwater runoff
- enhanced sound insulation
- enhanced carbon sequestration
- enhanced gaseous and particulate pollutant capture
- fostered biodiversity, and
- potentially enabled treatment of wastewater (YourHome, n.d.)

Having green spaces is becoming more pressing due to increasing urbanisation across society. In 25 years, more than two-thirds of the world's population will live in urban areas (UN DESA, 2018). Urbanisation is a complex socio-economic process that involves the transformation of the built environment, converting formerly rural spaces into urban settlements as people shift to metropolitan areas. It affects dominant patterns in occupations, lifestyles, cultures and behaviour, highlighting the rationale for quickly implementing change.

As Australian cities grow, planners and designers have an opportunity to create sustainable and adaptive urban environments to meet the needs of current and future generations (Department of Infrastructure, Regional Development, Communication and the Arts, 2024). The federal government is, therefore, developing a final **National Urban Policy** and guide for making cities more liveable, equitable, productive, sustainable and resilient. They are gathering input for spatial planning, which will lead to better management of transport, trade and information flow. This will require integrating advanced technology into construction processes to help prepare society for smarter, sustainable growth.

Designing eco-villages and precincts

Eco-villages are emerging worldwide as low-carbon or carbon-neutral neighbourhoods of the twenty-first century (Sherry, 2019). Typically, they have several features such as water and energy-efficient systems, gardens designated for communal spaces and to foster biodiversity, natural sources of heating or cooling for ventilation and insulation, embedded smart technology in nearby transport networks (light rail and electric buses) and charging stations for electric cars, storage for bikes and footpaths or footbridges and open spaces integrated with public and private spaces. New developments have also been trialled as eco-precincts to reduce our cities' footprints while improving the liveability of an area, to focus on change at a higher precinct level (Bunning et al., 2013).

Bioarchitecture in larger public projects

Bioarchitecture is a multiscale approach that uses the solutions and opportunities existing in nature to solve universal human problems (Ripley & Bhushan, 2016). It comes from direct bioinspiration and derived bioinspiration. Bio-inspired design methods include biomimetic, biophilic, bionic, biornametics and biomorphic strategies.

Cradle-to-cradle design, which is a biomimetic framework for designing buildings, was introduced by chemist Michael Braungart and architect William McDonough (2009) and has been widely adopted across disciplines to solve problems. Under this concept, every resource can become revalued as an asset for another purpose. In nature, the 'waste' of one system becomes food for another. Through design for disassembly, resources can be safely returned to the soil as biological nutrients or reutilised as high-quality materials for manufacturing new products, thus as technical nutrients without contamination.

Figure 14. Eastgate Centre, Harare, Zimbabwe
Source: Pearce (2016)

In the built environment, nature serves as the inspiration to create innovative and sustainable architectural solutions. Biomimetic models emulate forms, processes, systems and strategies found in nature. Architect Mick Pearce chose to adopt a **biomimicry style** of architecture and explains how the Eastgate Centre (in Harare, Zimbabwe), shown in Figure 14, borrows ideas from natural designs of wasp nests to keep the shopping centre cooler. Accordingly, the Eastgate Centre is an expression of two architectures: the revitalised order of brick and reconstructed stone and the old order of steel and glass. The new order moves away from the international glamour of the pristine glass tower archetype towards a regionalised style that responds to the biosphere, to the ancient traditional stone architecture of Great Zimbabwe and to local human resources. In the new order, massive protruding stone elements not only protect the small windows from the sun but also increase the external surface area of the building to improve heat loss to space at night and minimise heat gain by day. These are made of precast concrete, brushed to expose the granite aggregate that matches the lichen-covered rocks in Zimbabwe's wild landscape. The horizontal protruding ledges are interrupted by columns of steel rings supporting green vines to bring nature back into the city. The model used was a termitary ecosystem, not a 'machine for living in' (Pearce, 2016).

Planning for renewal and reconnection of existing buildings using **biophilic design** is another popular method to recreate sites to connect people and nature within built environments (Cacique & Ou, 2022). Designers strive to create multi-generational, multipurpose buildings devoid of urban density or traffic congestion, as evidenced by pedestrian-only shopping centres or roads constructed with increased bike laneways.

Adaptive reuse in communities

Adaptive reuse can also contribute to the sustainability of the built environment by preventing the wasteful process of demolishing and reconstructing new buildings. It is a key design strategy called for to meet the extreme need for affordable, social housing and be a tool for climate change mitigation (Aigwi et al., 2023). By changing individual or joint disused or ineffective buildings to another purpose (see Figure 15), adaptive reuse has the capacity to transform older construction into a renewable resource (Department of the Environment and Heritage, 2004). This circular process for urban renewal usually involves increasing housing density while preserving the character of neighbourhoods and improving amenities with variable floorplans.

Figure 15. Adaptive reuse of former Parcels Post Office, Railway Square, Sydney, now an Apartment Hotel
Source: Gorrey (2022)

It is not easy to execute an adaptive reuse project. Issues may arise at the onset related to planning and zoning, historical property laws, sensitive cultural matters and construction considerations. When converting office space to residential apartments, access to external walls can be a major issue as open-plan office spaces are widely used. Floor plans that are too deep cause problems in providing daylight when converting to residential apartments. Rules may change about which materials are allowed to be kept or used and disruptions can occur during construction stages. However, adaptive reuse can be a worthwhile pursuit because the practice has far-reaching, positive impacts (BG&E Engineering, n.d.). Moreover, refurbishment achieved by grouping buildings for medium density living offers personal and common areas for utilitarian and leisure activities. It lowers emissions in C&D, requiring less manufacture and transport of waste or building materials and it can be cost-effective (Aigwi et al., 2023). Local and state governments can support this agenda through policies and incentives for developers that, in turn, can create a master plan to support such upgrades (Fernández-Abascal & Grau, 2022).

Built heritage conservation is an exhaustive form of adaptive reuse. Under strict laws, owners must comply with preserving heritage landmarks. It is acknowledged for retaining certain materials, the façade, and the integrity and structure of a site, although most or all interior is transformed and modernised (Merlino, 2018).

From cradle to cradle

The literature advocates for the monitoring of resource flows (Talla & McIlwaine, 2024), which not only facilitates the tracing of resources but also supports the integration of CE principles in diverse areas, such as sustainable end-of-life strategies, material passport development, circularity assessments and the establishment of material banks. In addition, the implementation of smart demolition and selective dismantling is essential (Elghaish et al., 2022). Accordingly, the literature highlights the role of demolition contractors in identifying economic demand, devising appropriate disassembly routines and ensuring performance control until integration into a new building (van den Berg et al., 2021).

For example, the ***Circular Construction Evaluation Framework*** is a potential framework for quantifying circularity levels, enabling new designs that minimise waste and enhance salvage value (Dams et al., 2021). Similarly, Talla and McIlwaine (2024) propose strategies to maximise design quality, encompassing considerations for indoor climate, energy efficiency, daylighting and site-specific aspects. Talla and McIlwaine (2024) further introduce design considerations that aim to slow down and eventually close the resource loop, advocating for a comprehensive approach to sustainable resource management.

Regarding resource flows, the flow of energy usage throughout the lifecycle of buildings is critical to meet energy targets and improve energy efficiency, because the building sector's footprint is largely driven by energy consumption. This applies to all stages of a building's lifecycle, including construction, use, maintenance, renovation and demolition. While strategies have been developed to reduce energy use in homes, substantial emissions are generated during construction processes. These emissions result from raw material extraction, processing, manufacturing, transportation, on-site delivery and various supply chain processes. These are embodied emissions, whereas operational emissions arise from activities like space heating, water heating, lighting and appliance use in buildings. Embodied emissions play a significant role in the total carbon emissions over the lifecycle of a building and it is important to understand how to address them (Ibn-Mohammed et al., 2013). Figure 16 shows the life cycle of a building, including embodied and operational energy.

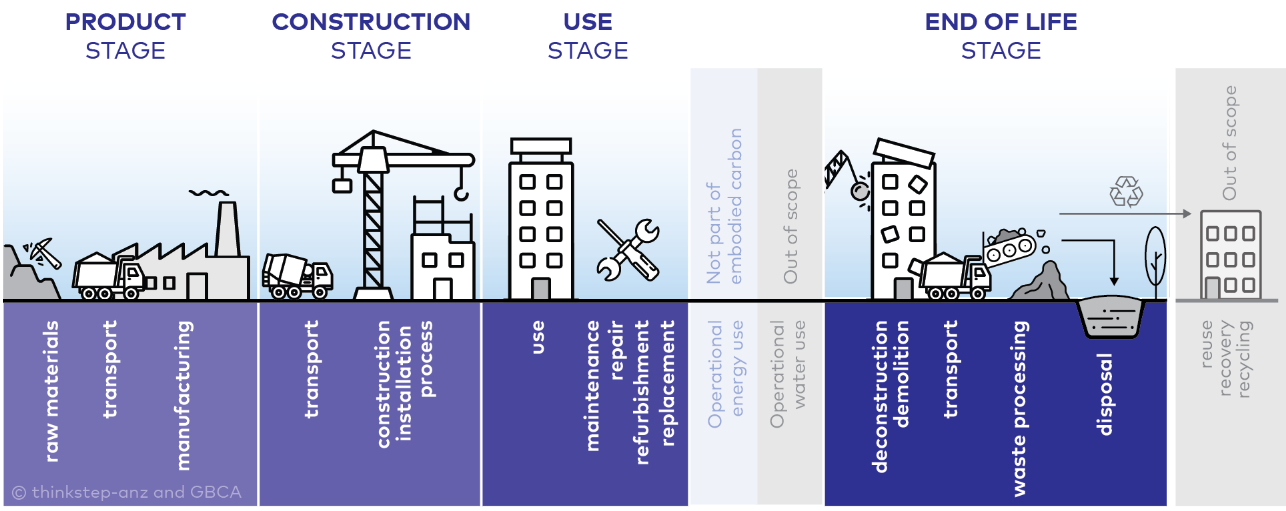


Figure 16. Life cycle of a building: embodied and operational energy
Source: Vickers et al. (2021)
CC thinkstep-anz

Environmental Product Declarations (EPDs) and **Life Cycle Assessments (LCAs)** are key tools relevant to materials and the advancement of circular supply chains in the built environment.

Environmental Product Declarations

Currently, the steps to obtain an LCA and then an EPD for a product or service are lengthy and complex. Yet, these environmental declarations are important because they provide quantified, independently verified environmental information about goods and services. Having transparent data about the environmental sustainability of a manufacturer's products allows buyers to make informed and better purchasing decisions (Del Borghi, 2013).

When LCA and EPD data are available, there is an opportunity to change extraction patterns through maintenance and repurposing (Vigovskaya et al., 2017), such as supporting carbon emissions reduction within the construction industry. Because EPDs are formal reports of a material's environmental footprint, they can also be used to help control building waste and encourage extended life cycles of building materials at the specification stage. In addition, making informed product choices can help developers stand out in the competitive property market.

An EPD can be broken down into two sections:

- the background project report, which includes a systematic summary of the LCA; and
- an EPD report containing data and results to be shared with the public.

The comprehensive LCA report documenting the environmental impacts of a product need to meet ISO 14040 and ISO 14044 principles, follow those methodologies and be verified by an independent party that specialises in LCA and EPDs. Results of the LCA study must be compiled in an EPD reporting format based on the ISO 14025 standard and must meet the principles and methodology for verification by an independent third party. Then, this party performs an LCA Environmental Impact Analysis. Once verified, both the LCA and EPD must be registered and published (Del Borghi, 2013).

EPDs for specifying reused materials allow materials to be deconstructed, certified and reused on new projects to lower carbon emissions, but regulations and markets must provide further support for circular materials (Skinner, 2023). The quality of LCAs in Australia currently suffers from the lack of specific data sets for Australia, e.g. data sets from other regions such as Europe need to be used instead.

Lifecycle Sustainability Assessment

Life Cycle Sustainability Assessment (LCSA) includes wider social and economic as well as environmental aspects that are important for business and society and for alignment with CE. LCSA is crucial in this regard but is still underdeveloped and not widely applied in the building industry (Wong & Zhou, 2015).

LCSA is defined in two primary ways. Klöpffer's (2008) LCSA methodology sees LCSA as an aggregation of environmental LCA, Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA) without formal weighting between them. Alternatively, the United Nations Environment Programme or UNEP LCSA Framework integrates these components into a unified framework that includes economic and social aspects, offering a more comprehensive sustainability evaluation (UNEP/SETAC, 2011). While the UNEP framework provides detailed guidance and enhances stakeholder engagement, it demands significant data integration, posing complexity and reliability challenges. In contrast, Klöpffer's model, noted for its theoretical rigour and flexibility, lacks detailed practical guidance and may not sufficiently emphasise social aspects, potentially overlooking important sustainability dimensions.

Although LCSA is beneficial for informed decision-making across various sectors, it has yet to be fully integrated or widely adopted in building projects (Pizzirani, 2014). Further development and refinement of LCSA methodologies are essential to address emerging needs and provide a unified approach to sustainability assessments. Potential areas for future development include investigating particular challenges and limitations of conducting LCSA within the building industry.

Challenges in data availability significantly impact the scope and accuracy of S-LCA and the associated impacts of conducting an LCSA. Key issues include a lack of standardised social indicators (the absence of consistent metrics), data scarcity and accessibility issues (even when data exist, they may not be readily accessible to researchers and practitioners due to confidentiality concerns of different organisations).

The evolving nature of social norms necessitates continuous updates to remain relevant, adding further complexity to conducting comprehensive S-LCA. There is still limited practical guidance on conducting an LCSA, which could be a barrier for new practitioners.

There is still a limited number of case studies available, making decision-makers less informed and thus motivated to conduct such analysis. In addition, the social aspect of LCSA is the least developed part, although there is evidence of social aspects in construction projects. The social concept is challenging to define and evaluate, partly because it is often abstract and not easily observable (Pizzirani, 2014). Thus, while the literature around LCA and LCC is more robust Costa et al., 2019) additional research is needed to develop S-LCA indicators for the industry. One potential avenue is embedding these indicators into Building Information Modelling (BIM).

BIM has demonstrated significant potential for conducting LCA. Various frameworks and plugins have been developed to integrate BIM and LCA, with state-of-the-art reviews indicating that BIM is effective for preparing the bill of quantity and collecting raw data on construction materials to conduct LCA (Obrecht et al., 2020). The primary focus has been on data integration between BIM models and LCA frameworks and recent literature reveals more automated approaches (Tam et al., 2023). This trend will likely extend to LCSA, although the S-LCA component requires further development, including creating new impact categories (Larsen et al., 2022). Further, new data structures are needed to enable BIM to effectively conduct LCSA during the design phase and to incorporate social and community impacts (Filho et al., 2022). Research suggests that Industry Foundation Class (IFC), a standardised digital description for built assets that allows different BIM software to read BIM models, will require the definition of exchange requirements and semantic rules for implementing LCSA (Llatas et al., 2022). Consequently, applying IFC to develop BIM-LCSA frameworks is a crucial direction for future research. For example, Boje et al. (2023) proposed a framework to integrate conventional LCSA using digital twins using a real office building as case study. Further, automation tools like Dynamo, Python and C# scripts, which have facilitated data gathering and integration for BIM/LCA integration, also show promise for BIM/LCSA integration. These tools can be leveraged to streamline processes and enhance the effectiveness of BIM in conducting comprehensive LCSAs.

Further, integrating BIM with LCSA can be significantly enhanced using Multi-Criteria Decision Making methods. Literature showcases this integration (Dong et al., 2023; Figueiredo et al., 2021) by combining environmental, social and economic assessments based on European standards. BIM is used to measure materials and simulate lifecycle impacts, while the Fuzzy Analytic Hierarchy Process (FAHP) serves as the Multi-Criteria Decision Making method. This method evaluates and optimises building design by prioritising materials and methods within BIM. The process includes defining project features, setting boundaries, identifying impacts, conducting LCAs and applying FAHP to determine the best sustainable design choices. This approach can greatly improve sustainable practices in construction. Thus, future research should investigate these methods and their potential for developing easy-to-use tools and plugins for BIM workflow that can be used by non-expert users. For example, if BIM models can be provided at completion and maintained through the life of a building, they could then provide the data required for urban mining.

Industry 4.0 technologies

Integrating technologies, such as the innovations of the fourth industrial revolution or Industry 4.0, provides key benefits to the construction industry to enable CE principles. The resulting Construction 4.0 marks a new wave of innovative solutions.

To support the integration of circular principles and supply chain optimisation, emerging digital opportunities of Industry 4.0 (I4.0) mark a paradigm shift towards a more connected and sustainable construction ecosystem (Elghaish et al., 2022). The integration of digital technologies across various industries, encapsulating a cyber-physical system approach, is a defining characteristic of I4.0 or the fourth industrial revolution (Maskuriy et al., 2019; You & Feng, 2020). This paradigm, commonly referred to as smart manufacturing, is particularly widespread in the manufacturing and production sector (Karmakar & Delhi, 2021). At its core, the fundamental driver of this transformation is the integration of virtual and physical processes in businesses (Sawhney et al., 2020). This digital revolution extends its reach to the construction industry, where advanced digital tools are making a significant impact, reshaping traditional approaches and methodologies (Talla & McIlwaine, 2024). The convergence of these technologies introduces a new age of efficiency, connectivity and transformative possibilities.

Construction 4.0

‘The equivalent adaption of automation and digitisation in the Architectural, Engineering, Construction, and Operations (AECO) industry is Construction 4.0’
(Karmakar & Delhi, 2021, p. 527)

Construction 4.0 emerged as a pivotal concept, originating in the first decade of the 21st century and officially defined in 2016 (Forcael et al., 2020; Karmakar & Delhi, 2021). This paradigm signifies the strategic integration of digital technologies into the construction sector (Craveiro et al., 2019), aiming to foster rapid growth and enhance profitability (Karmakar & Delhi, 2021). Implementing Construction 4.0 offers substantial opportunities for more efficient production, new business models and optimised value chains (Sawhney et al., 2020). The fundamental design principles of Construction 4.0 encompass information transparency, decentralised decision-making, seamless information flow, technical assistance through robotics and automation, and interconnectivity and interoperability. This transformation requires a more coordinated and collaborative approach (Karmakar & Delhi, 2021).

The adoption of Construction 4.0 can occur through two primary mechanisms. The first one is a grassroots adoption based on the value proposition offered by technologies. Although grassroots adoption is viewed as a more organic strategy, it is also more challenging in the fragmented construction sector. The second option is a top-down, policy-driven and mandated transformation imposed through regulatory frameworks (Karmakar & Delhi, 2021). Examples of the top-down policy-driven transformation include the case of BS-1192 in the UK, which directed the construction industry towards BIM and the establishment of international standards like ISO-19650 in 2018 (Karmakar & Delhi, 2021), which is *‘an international standard for managing information over the whole life cycle of a built asset using building information modelling’* (The British Standards Institution, 2024). Accordingly, these standards can provide the basis for regulatory measures and serve as catalysts for the industry-wide adoption of Construction 4.0, steering the sector toward a more technologically advanced and interconnected future.

Construction 4.0 represents a transformative integration of key I4.0 technologies, such as the Internet of Things (IoT), computer-aided design technologies, 3D printing, big data, artificial intelligence, robotics and virtual and augmented reality (Forcael et al., 2020). The technologies collectively form the pillars of innovation, enabling a comprehensive digital revolution within the construction industry. These key concepts can be implemented and organised into physical and virtual layers (Sawhney et al., 2020).

Implementation of Construction 4.0

The literature discusses various ways and frameworks to implement Construction 4.0, which depict the evolving landscape, showcasing the integration of digital technologies, data management and innovative approaches to enhance efficiency, sustainability and collaboration in the construction industry. The following examples provide an overview of how I4.0 can be implemented in the industry.

Two papers (Sawhney et al., 2020; You & Feng, 2020) have conceptualised frameworks for cyber-physical systems in construction. The framework of You and Feng (2020) presents a flexible and reconfigurable physical part emphasising plug-and-play construction resources (Figure 17). The IoT links the physical and cyber parts for vertical integration and the cyber part, located in the cloud, serves as a platform-as-a-service for big data storage, BIM and real-time construction. Then, a digital twin seamlessly maps physical and cyber components. In another example, Sawhney et al. (2020) discuss a five-layered technology framework for Construction 4.0, including a cyber-physical layer for data acquisition, data processing, a computational layer for modelling and simulation and decision support enablers and functional and visualisation.

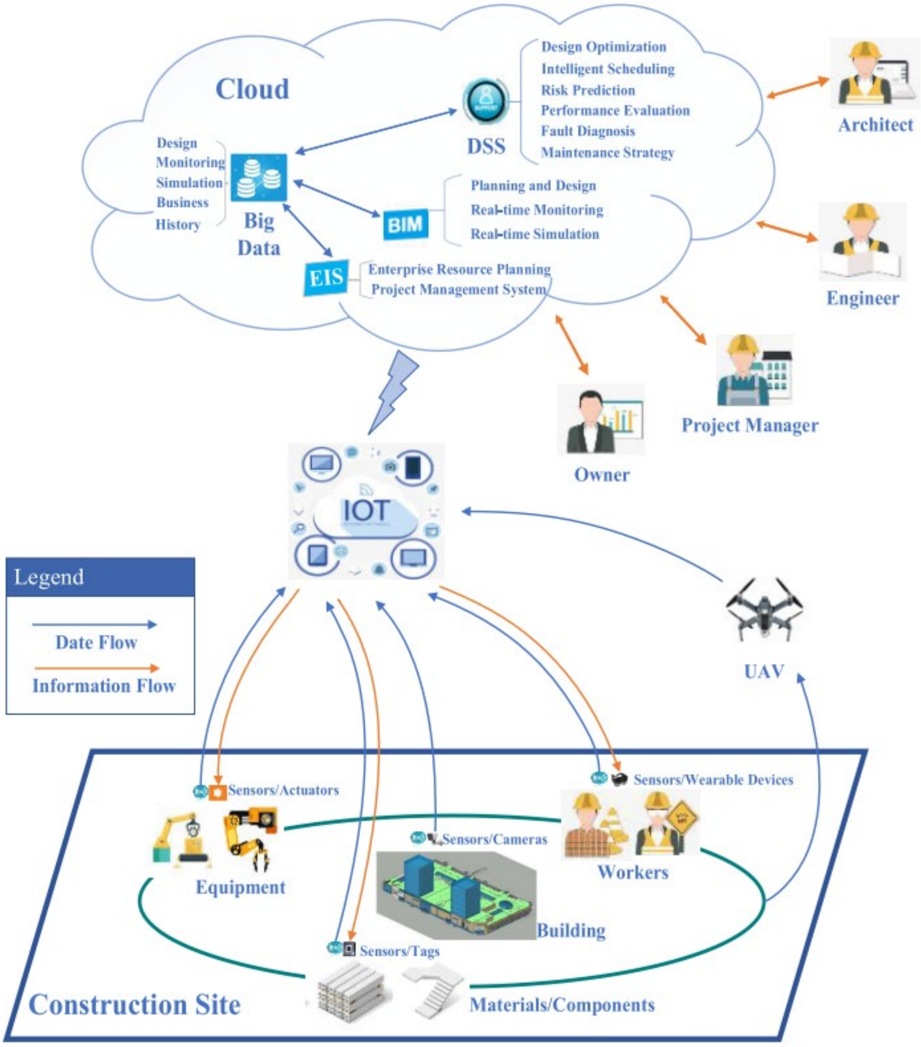


Figure 17. Overall framework of the cyber-physical system
Source: You and Feng (2020)

Karmakar and Delhi (2021) presented Construction 4.0 as a four-layered model, including a physical layer and three digital world layers. Their framework includes a core layer representing the final constructed facility (the physical reality), three digital layers (data layers, such as BIM, digital tools layer and core data management) and a continuous network of interactions. In addition, the authors conceptualised an integrated People-Process-Technology framework, covering Design, Documentation, Construction, Operations & Maintenance and Renovation/Demolition phases. Their work underlines the increasing amount of information created and transformed in the project's data layer. The framework also points to the continuous and complex network of interactions across all layers.

In their conceptual illustration of Construction 4.0, Setaki and van Timmeren (2022) focus on digital technologies throughout the construction lifecycle. They include disruptive technologies during design and engineering, construction, use and maintenance and demolition (Figure 18).

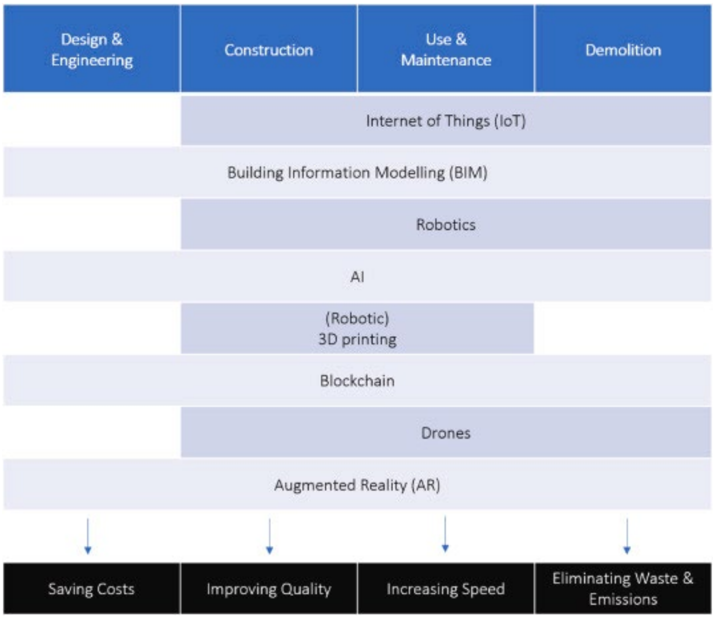


Figure 18. Digital technologies throughout the construction lifecycle and the corresponding benefits
Source: Setaki and van Timmeren (2022)

These examples provide a better understanding of how and which technologies to use in each phase of the construction lifecycle, thus facilitating the implementation of such technologies and data-driven, innovative solutions. Setaki and van Timmeren (2022) claim that the data-centric approach aims to contribute to innovative circular concepts within the building industry, focusing on material reuse, preserving material value through various applications and implementing strategies enabling high-quality recycling.

Construction 4.0 and the circular economy

Construction 4.0 could be a game-changer in enabling CE principles in construction. Setaki and van Timmeren (2022) conducted comprehensive research, examining applied examples of the technologies. Figure 19 summarises how the technologies can contribute to the CE. A detailed presentation of key I4.0 technologies and their role in the CE is shown below.

Building Information Modelling

BIM stands at the forefront of analysis because its integration with construction activities has become a valuable tool for tracking progress (Chen et al., 2022). It is often linked and integrated with other sensing and intelligent technologies (Wang et al., 2020). For instance, it plays a central role in the construction industry's journey to create digital twins (Karmakar & Delhi, 2021). Acting as the core for bi-directional coordination between the physical and cyber worlds, it excels in digitising and controlling the overall construction lifecycle (Maskuriy et al., 2019). Notably, its origins in Asia and Europe have paved the way for developing policies driving digital transformation within the built environment (Chen et al., 2022).

BIM marks a significant shift in the construction industry's approach, transitioning from a 'react to event' to 'predict the event' (Maskuriy et al., 2019). BIM serves as a revolutionary tool, empowering architects to elevate the effectiveness of the construction industry by creating sustainable and environmentally friendly building models (Sun et al., 2021). With its ability to construct green buildings, BIM can visually present essential information through 3D simulation modelling of the architectural landscape. In contrast to traditional methods, this innovative approach facilitates early design considerations that include energy and performance analyses for architectural design and construction. By evaluating aspects such as building materials, settings and technical support, BIM plays a pivotal role in advancing the industry's commitment to sustainability and efficiency (Sun et al., 2021). For instance, BIM assumes a crucial role in shaping strategic approaches for C&D waste management, encompassing reduction, reuse, recycling and landfilling (Karmakar & Delhi, 2021).

Table 3
Overview of technologies and examples discussed.

	Project name	Technology	Operation	Building Phase	Material Family	TRL	Application	CE value
3.1.1. a	Oris	IoT	Optimisation of maintenance	All phases, particularly in construction & maintenance	All materials	4–5	Digital materials platform	Maximises product use
3.1.2. a	Madaster	BIM	Optimisation of material flows	All phases, particularly interesting in demolition	All materials	7–8	Material passport	Recovery of by-products and waste
3.1.3. a	Circular experience	Robots	Reuse of waste wood	Construction/Demolition	Wood	7–8	Interior architecture	Recover oof by-products and waste
3.1.3. b	Rock Print Pavilion	Robots	Dry assembly	Construction/Demolition	Rock, twine	3–4	Temporary pavilion	Recover of by-products and waste
3.1.3. c	Wood Chip Barn	Robots	Reduction of waste	Construction	Natural shaped wood	5–6	Temporary pavilion	Recover of by-products and waste
3.1.4. a	AMP Cortex	AI	Sorting demolition waste	Demolition	Demolition waste	7–8	Sorting facilities	Recover of by-products and waste
3.1.4. b	Mine the Scrap	AI	Reuse of scrap	Design & Construction	Scrap materials	3–4	Classifying and reusing scrap materials	Recover of by-products and waste
3.1.5. a	Casa Covida	3D printing	Local soil	Construction & Demolition	Earth	5–6	Small scale architecture	Renewable inputs (resource efficiency)
3.1.5. b	Vertico 3D Concrete Printing Bridge	Robotic 3D printing	Optimisation of material usage	Construction	Concrete	7–8	Infrastructure/bridge	Renewable inputs (resource efficiency)
3.1.5. c	ARUP's metal 3D printed knot	3D printing	Optimisation of material use	Construction	Metal	5–6	Building component	Renewable inputs (resource efficiency)
3.1.5. d	Print Your City	Robotic 3D printing	Waste material, locally sourced	Construction & Demolition	Household plastic waste	7–8	Street furniture	Recovery of by-products and waste
3.1.6. a	Circularise	Blockchain	Digitises and traces materials	Construction & Demolition	All materials	7–8	Online platform	Recovery of by-products and waste
3.1.7. a	Mud Shell	Drones	Local soil	Construction	Clay	3–4	Shell	Renewable inputs (circular sourcing)
3.1.7. b	Flight Assembled Architecture	Drones	One material, dry assembly	Construction	Brick	3–4	Exhibition	Renewable inputs (circular sourcing)
3.1.8. a	Kitrvs	AR/VR	On-site complex fabrication	Construction	Brick	7–8	Facade	Renewable inputs (resource efficiency)
3.1.8. b	Fologram	AR/VR	On-site complex fabrication	Construction	Various materials	7–8	Platform	Renewable inputs (resource efficiency)

Figure 19. Construction 4.0 benefits for a circular economy with examples
Source: Setaki and van Timmeren (2022)

Moreover, BIM can be seamlessly integrated with other technologies to amplify its central nature in the construction landscape. Integrating BIM with complementary technologies refines the construction process and contributes to sustainable waste management practices. This synergy fosters a holistic approach that aligns with environmental goals, emphasising balanced and responsible handling of C&D waste throughout the project lifecycle (Karmakar & Delhi, 2021; Maskuriy et al., 2019). BIM can be integrated into the cloud to enable stakeholder collaboration in real-time from different locations to improve decision-making and address project deliverability. This enables comprehensive data on building components, aiding material reuse and recycling (Maskuriy et al., 2019). Further, BIM can be integrated with augmented and virtual reality, as well as IoT, to deliver countless significant incentives that cannot be attained by approaching them individually (Chen et al., 2022). Integrating BIM and IoT is also a trend mentioned by Elghaish et al. (2022), emphasising the importance of two-way communication between the built asset and the BIM model. In addition, the concept of a smart product-service system for prefabricated housing production, discussed in Talla and McIlwaine (2024), showcases the potential of these technologies in revolutionising the production process.

In another example, Akinade and Oyedele (2019) propose a hybrid BIM-based computational tool for building waste analytics and reporting in construction supply chains. Integrated as an add-in for Autodesk Revit, this tool exemplifies the potential of technology in advancing waste management practices. Moreover, the concept of CE-enhanced traditional LCAs is explored by Elghaish et al. (2022). They exemplify BIM for energy simulations, estimating operating costs, developing circular design alternatives, ranking these alternatives and tracking and updating LCAs by implementing digital twin technology.

Material passports

Addressing the lack of knowledge on materials at the end of life is crucial for promoting effective reuse and recycling in building practices, as emphasised by Talla and McIlwaine (2024). To overcome this challenge, the literature introduces the concept of Material Passports, which serve as a comprehensive system for digitally recording data sets related to an object. Material Passports describe the features, location, history and ownership status of materials in varying levels of detail, depending on the scope of usage. Managed via BIM or a portal, Material Passports are produced at multiple layers—city, structural, commercial and material levels. This innovative approach facilitates the closing of resource cycles by providing a comprehensive and accessible record of the materials used in a building.

The implementation of Material Passports offers several advantages. One key benefit is the ability to expedite material segregation and collection for reintroduction into the supply chain. By digitally recording and managing materials-related data, Material Passports streamline identifying, segregating and reusing materials, and contribute to more sustainable construction practices. Furthermore, Material Passports enable the tracking of the use of recycled materials. This functionality aligns with CE goals by promoting transparency in material sourcing and encouraging the use of recycled content in construction projects and support urban mining.

The consideration of construction waste in the selection of design alternatives is another noteworthy aspect of Material Passports, as highlighted by Talla and McIlwaine (2024). By incorporating information about the end-of-life implications of different design options, stakeholders can make informed decisions prioritising sustainability and waste reduction.

As shown in Figure 19, **Madaster** is an important real-world example. It is an online registry for documenting materials and products in building assets. By having access to every component, Madaster provides insights into the dismantling capacity, embodied carbon and toxicity of materials. It also assesses the materials' and products' ability to be reused. The Madaster Platform can be created based on a BIM or Excel spreadsheet and data input can enhance circularity outcomes. This solution is available in Europe, in particular, in Germany, the Netherlands, Switzerland and Belgium (Madaster, 2024; Setaki and van Timmeren, 2022).

Internet of Things

The Internet of Things (IoT) is based on devices or technology such as sensors, actuators, Radio-Frequency Identification (RFID), video cameras and laser scanners (You & Feng, 2020). Most current IoT solutions in the construction industry are limited to specific applications and there is a need for integrated multidisciplinary IoT data to support comprehensive monitoring, which contributes to the BIM model (You & Feng, 2020). The integration of the IoT in the construction industry holds significant potential, particularly when combined with BIM and digital twin technologies, as discussed by Elghaish et al. (2022). This combination enables a comprehensive understanding of asset performance, facilitating informed decision-making throughout the building's lifecycle. In the digital era, data is generated from the lifecycle of the building or structures, such as the phases of planning, design, tendering and bidding, construction, checking before acceptance and operation management. In this instance, data comes from IoT (You & Feng, 2020).

The Industrial Internet of Things (IIoT) takes IoT applications a step further, employing sensors to detect a broad range of information, including labour, carbon emissions and environmental factors (Elghaish et al., 2022). This real-time data collection offers valuable insights into the structural health of buildings, carbon emission quantities and energy consumption patterns. Such comprehensive information is instrumental in optimising various aspects of construction and building management. The role of big data is inherently evident in all technological applications, such as IoT, digital twins and BIM. Big data contributes to developing low-carbon, regenerative structures and aids stakeholders in decision-making. In addition, data mining can contribute to building energy performance.

Effective information management is crucial in the construction industry. The literature (Talla & McIlwaine, 2024) highlights various strategies and technologies employed to manage information flows efficiently. One innovative approach involves using RFID tags to simulate building elements. By incorporating RFID tags into building elements, designers can gain insights into the lifecycle of materials and investigate the potential for reusing goods from existing work sites. This technology facilitates the tracking and management of materials, contributing to more sustainable construction practices by promoting the reuse of resources.

The benefits of IoT and IIoT extend beyond individual buildings to impact entire companies and supply chain operations, as highlighted in the literature (e.g., Elghaish et al., 2022; Piyathanavong et al., 2024). By leveraging IoT technologies, organisations can identify their operations and supply chain bottlenecks, leading to enhanced efficiency and improved visibility. This is particularly relevant, considering challenges faced by the construction sector during the COVID-19 pandemic, such as workforce availability issues (Talla & McIlwaine, 2024). In addition, energy savings and increased asset utilisation are among the advantages brought about by IoT applications (Setaki & van Timmeren, 2022). Sharing assets, optimising material usage and enhancing maintenance and waste management practices contribute to more sustainable and resource-efficient construction processes. However, challenges persist and solutions are needed to seamlessly integrate IoT technology into existing buildings, allowing for the ongoing tracking of salvage value over time (Elghaish et al., 2022).

Digital twins

Several proposals have been put forth in the literature to enhance the remanufacturing process in construction. For example, Elghaish et al. (2022) suggest that digital twins can enable tracking, recycling and managing construction waste to facilitate its integration into remanufacturing. This approach aims to streamline the materials cycle, ensuring that discarded resources are effectively utilised and contribute to creating new products or building components. Digital twins also allow a cost-effective approach to resource tracking, scenario simulation and solution generation (Hu et al., 2022). Their integration opens a new paradigm in the industry to carry out intelligent construction (You & Feng, 2020).

The concept of predictive maintenance is presented as another strategy by Talla and McIlwaine (2024), demonstrating its potential to increase the service life of building materials. Construction stakeholders can use digital twins to identify and address potential issues before they escalate, prolonging building materials' life and reducing the need for premature replacements. This aligns with the principles of a CE by promoting durability and longevity in construction. Most importantly, the use of digital twins is not limited to the construction phase but extends throughout the deconstruction phase of a structure, as highlighted in Talla and McIlwaine (2024). This comprehensive approach recognises the importance of managing materials during their initial use and the dismantling and decommissioning stages, as well as maintaining a closed loop for materials.

The concept of a decentralised digital twin cycle, as discussed by Teisserenc and Sepasgozar (2021), adds another layer to the efficient management of construction processes. By implementing digital twins at various stages of a building's lifecycle, stakeholders can monitor, analyse and optimise performance. This decentralised approach ensures that each component contributes to the overall efficiency and sustainability of the construction process, fostering a holistic understanding and management of the building's lifecycle.

Artificial intelligence

In recent studies, integrating artificial intelligence (AI) in waste management processes has emerged as a promising avenue for enhancing efficiency and sustainability. The work by Wilts et al. (2021) explores the application of AI coupled with a robotic sorting system for effectively sorting bulky municipal material waste. This innovative approach not only improves the recovered materials recycling rate but also addresses concerns related to labour working conditions (Talla & McIlwaine, 2024; Wilts et al., 2021).

AI's capabilities extend further in waste management, as indicated by Elghaish et al. (2022). Implementing automatic and self-management of waste, utilising machine learning, allows for the classification and sorting of materials with a reliability percentage ranging from 90%-100%, particularly for reusable materials. This technological advancement has the potential to revolutionise waste sorting processes, contributing significantly to resource recovery and reduction in landfill usage.

Moreover, AI's reach extends into the early stages of architectural design. Talla and McIlwaine (2024) introduce a machine learning model to forecast the overall carbon footprint of regenerative building design alternatives. This assists architects in making informed decisions during the early design process, aligning with sustainability goals and reducing environmental impact. The convergence of AI with big data and the IoT emerges as a powerful combination, as highlighted by Talla and McIlwaine (2024). This synergy enables the prediction of system defaults, the detection of resource requirements and the forecast of future malfunctions. The predictive capability enhances resource proactive management, contributing to a more sustainable and resilient system.

On a broader scale, integrating AI in waste management and construction processes contributes to increased efficiency throughout the entire value chain. Setaki and van Timmeren (2022) emphasise the positive impact on monitoring and maintenance optimisation, demonstrating how AI technologies can streamline operations, reduce waste and enhance the overall sustainability of the construction industry.

Blockchain

Blockchain technology emerges as a key enabler in the construction and building sector, as noted in Talla and McIlwaine (2024). By functioning as a shared database, blockchain enhances transparency and accountability, contributing to the decentralised tracking of information such as material and waste flows. Beyond the initial design phase, the literature highlights the significance of maintenance and asset management for extending the lifetime of building assets (Elghaish et al., 2022).

Moreover, blockchain technological advancements serve to increase functionality, efficiency and visibility within the construction industry (Setaki & van Timmeren, 2022). The interconnectedness of stakeholders across different levels, whether at the enterprise, consortium, or public level, is of great importance (Teisserenc & Sepasgozar, 2021). This interconnectedness fosters collaboration and information exchange, creating a more integrated and sustainable construction ecosystem. Despite its potential, blockchain applications in the construction/built environment remain relatively limited (Elghaish et al., 2022).

Digital platforms and cloud services

The literature also underlines the importance of enhancing communication and collaboration within the supply chain. Talla and McIlwaine (2024) emphasise that information flow should extend beyond individual projects, involving seamless communication and collaboration among different participants in the supply chain. This interconnected approach optimises processes, reduces delays and enhances overall efficiency.

One notable example illustrating the effective management of information flows is the **EDGE Olympic office building in Amsterdam**. As Talla and McIlwaine (2024) described, the building incorporates an electronic version operating on a cloud service. This system allows users to personalise their work environment and dynamically utilise the space. Including such technology not only improves the functionality and efficiency of the workspace but also demonstrates how digital solutions can enhance user experience and operational effectiveness in a built environment.

Robotics and drones

Robotics are also known as construction automation technologies to create elements of buildings, building components and furniture (Maskuriy et al., 2019). The integration of high-precision assembly and automation, particularly through the use of physical robots, is a transformative aspect of the construction industry (Setaki & van Timmeren, 2022). This adoption can revolutionise workflows on building sites, aligning with the principles of the CE while offering increased accuracy and precision and reduced production time.

The deployment of robots in construction addresses various challenges by enabling the automation of labour-intensive, difficult, or repetitive tasks. According to Setaki and van Timmeren (2022), these tasks range from lifting heavy objects and placing them in exact coordinates to working with non-standard materials sourced from waste. The result is the production of building components with high accuracy, contributing to the creation of high-value structures. For example, versatile robotic arms can perform a wide range of tasks and provide custom solutions for each project. This includes laying bricks, executing complex assemblies with precision, especially in off-site manufacturing facilities and supporting sustainability principles such as sorting waste materials or assembling structures from waste sources.

Moreover, drones can offer additional benefits to construction processes. They facilitate onsite digital asset tracking, continuous spatial inspection and progress monitoring. This not only enhances project management but also promotes waste reduction by providing real-time data that can inform decision-making and optimise resource utilisation (Setaki & van Timmeren, 2022).

Augmented manufacturing and 3D printing

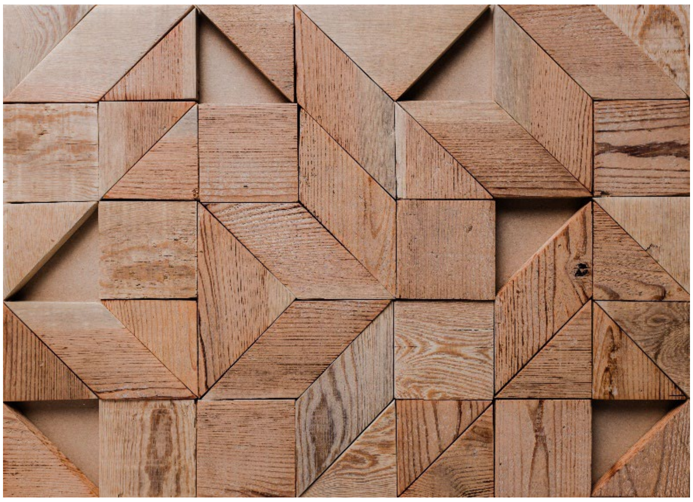
Efficient resource utilisation in construction is a key aspect of sustainable practices. This solution involves integrating various technologies, emphasising the importance of combining different tools such as 3D printing and IoT. One notable benefit of employing efficient resource utilisation strategies is the significant reduction in waste (Elghaish et al., 2022). Moreover, the literature suggests that the industry can make substantial strides towards more sustainable and environmentally conscious practices by streamlining construction processes and implementing technologies that minimise material wastage. The modular nature of construction elements also plays a crucial role in resource efficiency (Elghaish et al., 2022; Setaki & van Timmeren, 2022). Talla and McIlwaine (2024) discuss the customisation of connecting elements for structures, promoting a modular approach that facilitates reusability at the end of a structure’s life. For example, this approach extends to reversible wood beams that can be robotically assembled and dismantled, minimising the need for new materials and reducing overall waste.

Setaki and van Timmeren (2022) emphasise optimising material use, such as using recycled, recyclable and locally sourced materials to reduce transportation-related environmental impacts and exploring the potential for achieving zero-waste construction. By prioritising these considerations, construction practices can align more closely with sustainability goals and contribute to the broader movement towards circular and resource-efficient economies.

In general, new technological elements can support heritage and new construction projects. The installation of energy-efficient equipment, in particular, has become fundamental to facilitating improved practices towards achieving sustainable outcomes. There is already a large uptake of rooftop solar panels in new and refurbished structures. Integration of photovoltaic cells and nanoparticles in building materials and components (e.g., concrete, roof tiles, paint and glass), wind and geothermal microgenerators, adds higher performance heating, ventilation and air conditioning systems, LED lighting and smart building management detectors and systems to capture, analyse data and adjust building setting in real time for optimal energy use are becoming increasingly adopted and facilitated by technological tools (Martin & Perry, 2019).

Materials in construction

Traditional building materials are made from natural and synthetic elements. When appropriate, these materials can be replaced with better selections of bio-based alternatives or hybrids that can support the CE of buildings.



Primary conventional materials in use

Timber

Massive timber construction is emerging as a leading sustainable solution with greater uptake in major metropolitan areas of Australia. Martin and Perry (2019) contend that massive timber construction has evolved from traditional low-rise residential housing to large multi-story buildings across markets and can meet the industry's needs for sustainable solutions. Engineered timbers have been invented to reinforce the structural qualities compared with sawn timber for use in high-rise commercial and residential projects. For example, cross-laminated timber (CLT), glue-laminated timber (Glulam) or laminated veneer lumber (LVL) and laminated strand lumber have been made available as large, solid panels and columns for massive timber construction. These materials offer resource efficiency for improved sustainability in construction (Kuittinen et al., 2013).

This positive impact is attributable to wood's capacity to sequester and store carbon. One m^3 of wood can absorb approximately one tonne of CO_2. No other material has this absorption threshold (Lehmann, 2012). In addition, converting wood to produce construction materials requires less energy, resulting in lower carbon emissions than other materials. Of the engineered products, CLT has the lowest carbon footprint.

The source of wood is another extremely important factor in sustainability. Today, timber is predominantly logged from plantation forests that comply with stewardship schemes, generally offered through the Forest Stewardship Council (FSC) and The Programme for the Endorsement of Forest Certification (PEFC). For commercial buildings to be assessed for sustainability under the Green Star rating system, materials, including timber, are required to comply with stewardship schemes to qualify for timber credit points (Green Building Council of Australia, 2023).

At the downstream end of the supply chain, massive timber construction is linked to prefabrication and supportive digital technologies such as BIM and file-to-factory-to-site methodologies. Research using LCA shows these approaches enhance environmental outcomes over onsite construction (Kuittinen et al., 2013). For instance, prefabrication is advantageous because it uses less carbon during production than traditional construction processes. Then, advanced digital technologies enable the capacity to transfer BIM data to machines in factories to fabricate timber elements using widely used CADworks or Revit software for automated processing. Finished components are devised with metal connectors, delivered and assembled into complex, high-load structures on site (Martin & Perry, 2019).

As previously stated, additional massive timber construction projects have increasingly been delivered in large metropolitan areas of Australia since National Building Codes were modified in

2016 to ease height compliance of massive timber and engineered wood construction projects up to 25 m (Australian Building Codes Board, 2019).

Completing these projects is a testament to the rapid growth of massive timber construction across Australia. It also strengthens market confidence and helps attract capital investment to build economies of scale for broader growth in sustainable building.

KLH UK Ltd., for example, collaborated with Lendlease to streamline the construction of its Forté building in Melbourne by communicating design instructions via BIM technology to cut and fabricate panels offsite. The panels were shipped to a crane on site and a small group of carpenters assembled the building. Because Lendlease acted in multiple roles as a property developer, design manager and head construction contractor, it facilitated a quick project delivery (Martin & Perry, 2019).

Macquarie University's Clinical Education Building in Sydney, completed in 2019, brought to fruition the University's aim for longevity in choosing timber—a strong, everlasting material that incorporates biophilic properties and engenders positive, sustained interactions with the natural environment (Wilson, 1986) among students, staff and public alike. Other examples are found in the International House Sydney, Australia's first massive timber construction commercial office building, which was finished in 2017 and stands at the gateway of Barangaroo South. It was built with 1,750 pieces of CLT, glulam and recycled timber telegraph poles and was assembled with over 20,000 screws. Adjacent to it is the mixed-use waterfront urban renewal landmark, Daramu House, which translates as *treehouse* in the local Aboriginal language.

In another example, Atlassian will complete a 180 m high-rise hybrid timber commercial centre in Sydney in 2025. Operating on 100% renewable energy and net zero emissions, the building targets 50% less embodied carbon than traditional buildings while generating 50% less energy consumption over ten years. A steel and glass facade will hover over the exterior to support mega floors that adjoin neighbourhoods and feature large terraces for elevated public parks (BVN, n.d.). Similarly, Melbourne features an array of multi-purpose massive timber buildings: the Docklands Library (using CLT and Glulam); the Forté apartment complex (using CLT); the Adina Hotel at Southbank (a CLT vertical extension); the Fivex commercial space (a CLT and steel vertical extension); the Garden Building at RMIT (a timber concrete composite); Melbourne Connect (using CLT and Glulam); and the iconic T3 Collingwood (using CLT and Glulam) (WoodSolutions, 2024).

Developers have also secured approval in Perth to build the world's tallest hybrid tower. Rising to a height of 191.2 m, this biophilic-designed residential tower will consist of 40% timber beams, floor panels, joinery, linings and studs by combining durable and lightweight Glulam and CLT with LVL and lower quantities of concrete and steel than conventional construction. Edible and floral gardens will be grown on its rooftop. Architectural firm Fraser and Partners will make all technical materials from the project open access to encourage more massive timber construction in response to the climate crisis (Dumas, 2023). Nonetheless, there are limitations in finding suppliers to produce the needed quantum of timber and developers who will shoulder the costs that exceed conventional building.

Despite timber's renewable character and lower energy impacts, it is important to note many engineered wood products are created with petrochemically-based adhesives to form a structural bond between the layers of wood (Milner & Woodard, 2016). There have been developments that have brought sustainable alternatives to the market. Bio-based adhesives derived from lignin have been released (Aro et al., 2014) and a thermal modification technique can be applied for natural wood preservation (Wang et al., 2018).

Another consideration is that engineered wood products are often treated to resist decay from insects, rot or moisture (Shukla & Kamdem, 2012). They vary according to the performance of the wood and may be applied with chemicals, submersion, heat or radiation. Chemical treatment preservatives must be approved by the Australian Pesticides and Veterinary Medicines Authority. Quantities and concentrations are determined by Australian Standards AS 1604 (SAI Global Australia, 2024). Hence, any timber purchased from overseas may not hold the same scrutiny and could contain concentrations or substances deemed illicit. Even though Copper Chrome Arsenate (CCA) treatments, which are known to leach carcinogenic and heavy metals into soils and groundwater, are used, CCA timber should be avoided in favour of Copper Quaternary (ACQ) and Copper Azole (CuAz). All insecticide or treatments on The Living Building Challenge (LBC) Red List (International Living Future Institute, 2022) should be interrogated for safety.

While insect and fungal protection is imperative for structural integrity and CE, it can be better managed. Acetylation is non-toxic compared with conventional chemical treatments (Grace et al., 2020). Radiata pine, for example, can be soaked in acetic anhydride, an organic compound related to vinegar. It does not swell like regular wood; it looks good and tends to be durable, but the wood is treated overseas, so this source of embodied energy needs to be considered.

Timber durability classes relate to the natural ability of timber to resist decay and insects. Class 1 timbers are long-lasting and extremely durable. In protected indoor areas they can last 50+ years, in outdoor above ground areas 50+ years and in-ground areas 25+ years. Therefore, local and naturally treated class 1 timbers should be prioritised for construction in this manner whenever reasonably practicable. Class 1 and class 2 timbers can be left exposed, but untreated wood may leach tannins onto adjacent surfaces. Hence, an initial coating of natural oil helps to stabilise the wood and gives it antifungal protection (Tang et al., 2021). The wood will naturally turn grey over time but will be recyclable. If paint is applied, it is important to specify low volatile organic compounds (VOC) paints for interiors (Pacheco-Torgal & Jalai, 2011) because they are usually composed of resin, pigment, solvent and additives that tend to release VOCs and cause indoor air pollution. Common varnish is made of petroleum, alcohol, polyurethane, sodium hydroxide, formaldehyde, benzene, glycol ether and some may contain arsenic substances.

At a building's end-of-life, it is crucial to reclaim the timber and optimise how the wood can be best reused or recycled to prevent the emissions from being released through burning or rotting under aerobic conditions (Martin & Perry, 2019). Reusing and recycling timber for offsite construction are the key elements and most highly efficient strategies to enact CE principles in modern methods of timber construction (Ghobadi & Sepasgozar, 2023). To realise this outcome, focusing on design for efficient disassembly is called for by including reversible mechanical connections, independent building components and working with prefabricated structures (Klinge et al., 2019). Any residual timber in adequate sizes and quality conditions should be resold for cascading uses (Psilovikos, 2023). Subsequently, value can be added by allowing different users to source this secondary feedstock to create another product.

Polymers

Polymers have become integral to modern building construction, offering versatility across various applications. These applications range from waterproofing, exemplified by polyurethane coatings, to sealants (Galimzyanova et al., 2020), insulation through polyurethane foam (Das et al., 2023), roofing (Nasser et al., 2018) and even plumbing and electrical conduits (Neu & Hammes, 2020; Victoria Government, 2024). Polyvinyl chloride (PVC) stands out as the most crucial polymer in the construction industry due to its durability, technical versatility, performance and cost-effectiveness. PVC is applied in long-term applications such as pipes and fittings, cable insulation, floor coverings, window profiles, cladding and roof membranes. Over 60% of Australia's annual PVC production is used for construction and building applications.

In general, the appeal of polymers lies in their exceptional properties, including low weight, robust thermal and chemical resistance, durability and the potential for reuse and recycling. This has significantly contributed to the promotion of sustainability within the construction sector (Real, 2023). However, approximately 6% of the global yearly oil production is dedicated to the manufacturing of plastics, leading to the release of 850 Mt of GHG emissions—a consequence of both new plastics production and the incineration of discarded plastic waste (Dai et al., 2022; Foundation, 2016). In Europe, the demand for polymeric materials in building and construction has surged, accounting for

21% of total plastics consumption, translating to 10.3 million tons (EUPC, 2018). This substantial usage makes the construction industry the second-largest consumer of polymers, surpassed only by packaging. However, compared with packaging, plastics and polymers in buildings are in use for prolonged times (e.g. decades).

In the financial year 2018-19, Australia's plastic consumption was approximately 3.36 Mt. According to data presented in Table 6, only 4% of the consumed plastics contained recycled plastics and the recycling rate of plastics was only 14%.

Table 6. Circular economy indicators for plastics in Australia from 2018-19
Source: VDZ (2021)

Indicator	Value
Recycled content	4%
Collection efficiency	17%
Sorting efficiency	93%
Reprocessing efficiency	95%
Recycling rate	14%
Landfill rate	85%
Local material utilisation	9%

Figure 20 illustrates the stocks of plastic, and 3,922,900 tonnes of plastics were consumed in Australia, according to O'Farrell et al. (2024). A notable accumulation of plastics is observed in the built environment and durable consumer goods, while around one-third of plastics are utilised in applications with lifespans of less than one year, such as packaging (VDZ, 2021). Moreover, plastic consumption in Australia has consistently increased over the years, rising from 1.5 Mt in 2000 to 3.5 Mt in 2019 (Hossain et al., 2022) and 3.9 Mt in 2021-2022.

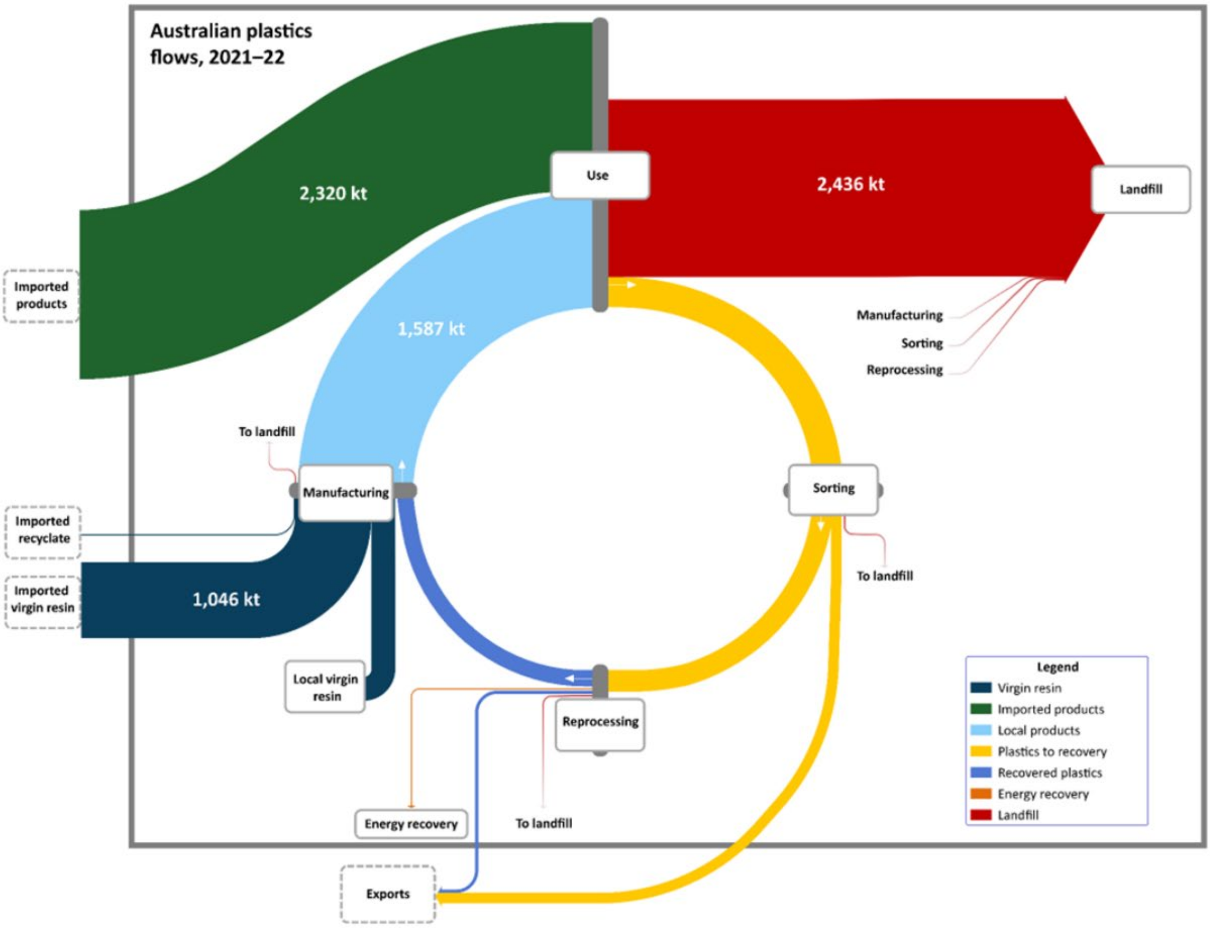


Figure 20. Plastic flows in Australia, 2021-2022
Source: O'Farrell et al. (2024)

Recognising the environmental impact, researchers worldwide are developing sustainable polymers with enhanced performance, degradability and recyclability, often exploring plant-based alternatives (Hong & Chen, 2019). Recent advancements in polymer research showcase innovative ways to repurpose waste materials. For instance, a study revealed that waste polyurethane foam can be used as a filler to manufacture polypropylene-based composites. These composites exhibit superior thermal insulation properties, with a remarkable 64% decrease in the thermal conductivity coefficient and a 68% reduction in density (Kowalczyk et al., 2023).

Moreover, waste polymers such as low-density polyethylene and PVC have applications in sustainable construction practices. Blending these polymers with fly ash and cement results in lower density, higher compressive strength and more cost-effectiveness than traditional bricks (Madghe et al., 2022). Similarly, polystyrene, in combination with unprocessed fly ash, has been employed to partially replace natural aggregate and ordinary Portland cement, producing lightweight concrete (Herki, 2017). The incorporation of recycled expanded polystyrene into concrete production emerges as a promising approach, further aligning with the overarching goal of promoting sustainability in the construction industry (Polyfoam, 2024).

In conclusion, polymers are pivotal in advancing the CE within the building and construction sector. These materials contribute to sustainability by being recyclable, enabling closed-loop systems that reduce reliance on virgin resources. Their durability and longevity promote a longer lifespan for construction materials, minimising the need for frequent replacements and reducing waste. Polymers also facilitate modular construction and prefabrication, enhancing efficiency and supporting disassembly and reassembly practices. In addition, their design flexibility fosters innovation in creating energy-efficient building components. The integration of polymers into closed-loop systems ensures that materials can be efficiently recovered and reused, aligning with CE principles and promoting resource conservation throughout the construction life cycle.

Metals—steel and aluminium

Steel and aluminium play crucial roles in building and construction due to their distinct properties. Steel, known for its strength, is widely used in structural framing, beams, columns, bridges, rebar for reinforced concrete and prefab construction. It is also used in steel studs, roofing and the construction of storage tanks (Jacinto et al., 2023). In contrast, aluminium, prized for its lightweight nature and corrosion resistance, finds applications in curtain walls, window frames, exterior cladding, railings and balustrades (Georgantzia et al., 2021; Illankoon et al., 2023). Aluminium composite panels are used for cladding and aluminium formwork enables efficient and reusable moulds in concrete construction (Aluminium, 2023). In addition, aluminium is employed in electrical wiring and various architectural features, including decorative elements and sculptures (The Aluminium Association, 2023a).

Steel is manufactured through two primary processes: the blast furnace-basic oxygen furnace (BF-BOF) route and the electric arc furnace route. The BF-BOF route relies on iron ore, coal and recycled steel as its main raw materials, constituting approximately 70% of global steel production. In contrast, the electric arc furnace route predominantly utilises recycled steel and electricity, contributing to about 30% of total steel production (International Energy Agency, 2020). However, the steel industry faces challenges, given its substantial energy consumption and high emissions which account for 7% of global CO_2 emissions in 2019 (International Energy Agency, 2020). Predictions suggest a yearly demand for 760 million tonnes of steel in building construction by 2050 (Deetman et al., 2020).

Efforts to decarbonise the steel sector involve technological advancements, with potential emission reductions of 96% by 2050 through technologies like green hydrogen or carbon capture, energy efficiency measures and increased steel scrap recycling (Speizer et al., 2023). Collaborative initiatives between the steel industry and users are crucial for upcycling scrap and reducing steel consumption (Watari et al., 2023). Moreover, addressing technological, economic and political uncertainties is essential for global decarbonisation (Hermwille et al., 2022).

Aluminium is a material that requires a significant amount of energy and chemicals for its production and is commonly utilised in the form of alloys (Pedneault et al., 2022). The alloying elements in aluminium include silicon, iron, copper, manganese and magnesium. Aluminium alloys can be categorised into two fundamental types: wrought and cast. Cast alloys are melted and poured into moulds, while wrought alloys undergo treatment in a solid state (Georgantzia et al., 2021; Pedneault et al., 2023). Aluminium production consumes 3.5% of the world's electricity and contributes 1% of global CO_2 emissions (Cullen & Allwood, 2013). A quarter of the worldwide aluminium production is utilised in the construction industry (Aluminium, 2023; Liu et al., 2013).

In the context of sustainability and efforts to mitigate climate change, recent technological progress has given rise to innovative structural systems using aluminium. Notably, advancements in manufacturing aluminium alloys have significantly cut energy requirements by over 75% since 1995, resulting in a nearly 40% reduction in the industry's carbon footprint (Georgantzia et al., 2021). In addition to reducing CO_2 emissions, structural aluminium alloys are entirely recyclable, making them a strong contender for the designation of 'green metal' (The Aluminium Association, 2023b).

Steel and aluminium are crucial in advancing the CE because both materials are highly recyclable, contributing to closed-loop systems that reduce the demand for new resources and minimise waste (International Aluminum Institute, 2009; Kanyilmaz et al., 2023). The recycling process for steel and aluminium is energy-efficient, making it environmentally favourable compared with primary production (Kanyilmaz et al., 2023). In addition, the durability and longevity of steel and aluminium in construction components, such as beams, columns and facades, support the principles of CE by extending the life cycle of building materials. The versatility of these metals allows for modular construction, facilitating easier disassembly and reassembly of structures and promoting sustainable practices.

Applied finishes to materials should be eliminated or avoided whenever possible to maintain material integrity and prevent human exposure to toxic substances. However, when metal finishes are chosen, fit-for-purpose is considered safer and has minimal environmental and social impact.

Chrome plating is a corrosive, dangerous material and a known carcinogen that relies on ample energy during application (Muller et al., 2022). Other metal coatings vary in energy intake, safety and waste production. Of the available choices, physical vapour deposition or powder coatings have the least environmental impact. However, while they do not use hazardous biocides, create toxic waste and meet rigorous environmental standards, they are energy intensive. The development of ultraviolet curable powder coatings is bringing further progress (Czachor-Jadacka & Pilch-Pitera, 2021).

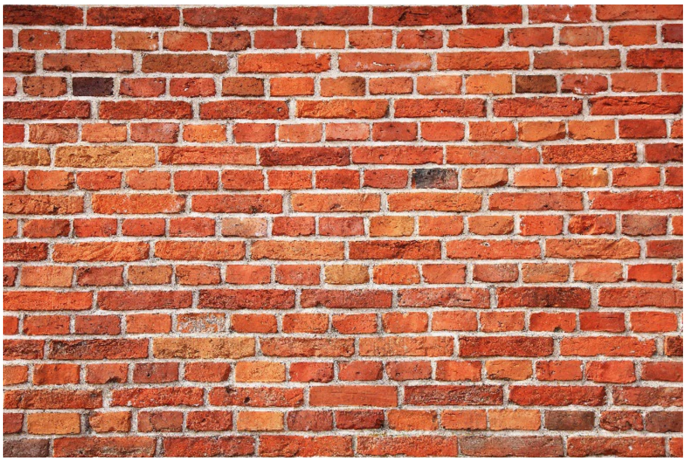
Stone

In building and construction, stone serves various purposes due to its durability, versatility and aesthetic appeal (Jones & Sainsbury, 2023). Common applications include using stone for structural elements such as walls and foundations and for cladding and facades to enhance a building's appearance and provide weather resistance (Cooper, 2019). Stone is also frequently employed for paving, flooring and retaining walls, contributing to functionality and landscaping (Antonio Biancardo et al., 2021). In addition, stone is used in decorative features, creating ornate carvings, sculptures and architectural details. Due to its enduring nature, it is a popular choice for fireplaces, chimneys, monuments and memorials. Stone is also utilised in landscaping projects, interior finishes like countertops and wall cladding and bridge construction, where certain types of stone, such as granite, offer strength and durability (Cooper, 2019).

Despite the historical dominance of Italian producers in the dimensional stone industry throughout the twentieth century, there has been a gradual shift, with Chinese producers now taking over. In 2017, Asian producers collectively contributed approximately 65% to the global production, whereas Europe accounted for about 15%. By comparison, in 1996, Asia and Europe held approximately 40% and 30% of the global production, respectively. Approximately 75% of dimensional stone products find application in building construction (Ericsson, 2019).

Stone plays a significant role in promoting the CE within the construction industry. As a natural and durable material, stone can be extracted, processed and used in projects with (partly) minimal environmental impact (Moore, 2023). Its longevity and resilience contribute to the sustainability of structures, reducing the need for frequent replacements and minimising waste. Stone's adaptability for reuse in various applications, such as cladding, flooring and landscaping, aligns with CE principles by extending the material's life cycle.

Bricks—mud and clay



Using mud and clay bricks in construction aligns with sustainable practices and offers a cost-effective, locally sourced building material with a rich history (Almssad et al., 2022). Their adaptability makes them suitable for various applications in diverse construction projects (Fiala et al., 2019). They serve as the foundation for structural walls (Maia de Souza et al., 2016), partitions (Magliulo et al., 2023) and stable foundations and are also used for external cladding, offering both aesthetic appeal and insulation (Ramadhan et al., 2022). Ideal for pathways, driveways and courtyards, mud and clay bricks are durable paving materials. With heat-resistant properties, they find application in fireplaces, chimneys and retaining walls, contributing to architectural details (Vasconcelos et al., 2023).

Various methods have been implemented over time to enhance the quality of bricks. Initially, sun-baked bricks were crafted using natural heat. To mitigate distortion and cracking, chopped straw and grass were introduced into the clay mixture. A significant advancement involved firing the bricks to enhance their strength and durability. Nevertheless, concerns have been raised about the energy consumption and GHG emissions associated with producing fired clay bricks. Therefore, to promote clay bricks as a sustainable construction material, incorporating agricultural and industrial waste materials emerges as a viable solution (Phonphuak & Chindaprasirt, 2015).

Numerous investigations, therefore, have explored the utilisation of diverse waste materials, encompassing both organic and inorganic substances (Raut et al., 2011; Zhang, 2013). These materials include, but are not limited to, residues from paper processing (Sutcu & Akkurt, 2009), kraft pulp (Demir et al., 2005), olive pomace (La Rubia-García et al., 2012; Sutcu et al., 2016), cotton waste (Algin & Turgut, 2008), wood sawdust (Turgut & Murat Algin, 2007), straw (Aouba et al., 2016), processed tea waste (Demir, 2006), cigarette butts (Kadir et al., 2009), sugarcane bagasse (Faria et al., 2012), rice husk ash (Görhan & Şimşek, 2013), fly ash (Lingling et al., 2005), limestone dust, marble waste (Sutcu et al., 2015), blast furnace slag (Malhotra & Tehri, 1996), metallurgical slag (Gencel et al., 2013), industrial wastewater treatment sludge, Bayer process bauxite waste (red mud) (Atan et al., 2021) and various biosolids (Ukwatta & Mohajerani, 2017). These studies have focused on their application in the production of brick bodies, aiming to achieve specific objectives such as lightweight construction products for insulation, reinforcement, waste reduction and recycling.

Despite extensive research, widespread commercial production of bricks from waste materials remains significantly constrained. The limited adoption of this practice can be attributed to several factors, including the methodologies employed in brick production from waste materials, the potential risk of contamination associated with the use of such materials, the absence of established standards and the gradual acceptance of bricks made from waste materials within both industry and the public sphere. Further research and development are imperative to facilitate the broad-scale manufacturing and application of bricks derived from waste materials. It should encompass not only technical, economic and environmental considerations but also address issues of standardisation, government policies and public education pertaining to waste recycling and sustainable development (Zhang, 2013).

Figure 21 illustrates the material flows into residential-detached construction in Australia from 1970 to 2020. After 1980, concrete and brick emerged as the predominant materials, collectively representing more than 90% of the weight of construction materials (Kempton et al., 2024).

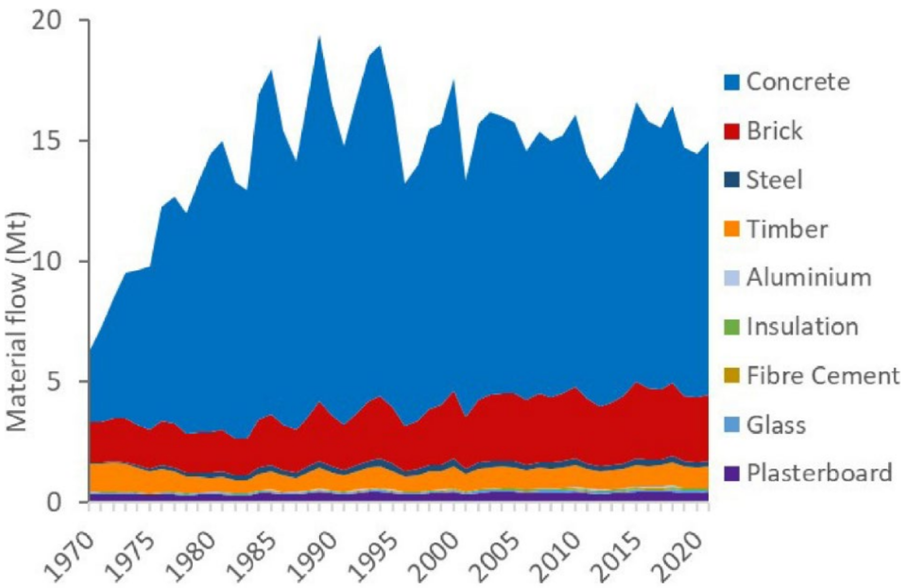


Figure 21. Annual estimate of material flow into residential-detached construction from the material flow analysis model for the period of 1970-2020
Source: Kempton et al. (2024), CC BY 4.0

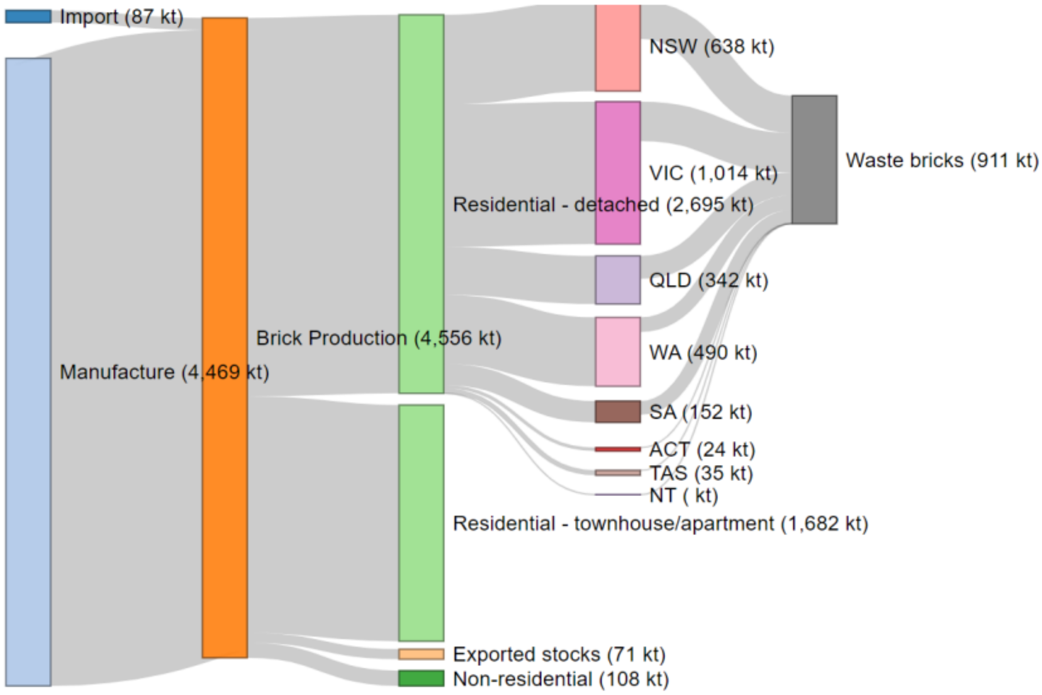


Figure 22. Brick manufacture, use and waste for detached residential housing in Australia using material flow analysis: 2019
Source: Dalton et al. (2023), CC BY-NC-SA 3.0

Figure 22 shows brick manufacture, use and waste for detached residential housing in Australia. This diagram uses models incorporating raw material availability and import/export industry supply-chain information. The figures presented are annual, offering restricted insights into the Australian industry regarding specific construction materials and their market applications, given that aggregated data is typically expressed in financial terms rather than volumes. Nonetheless, it is valuable in pinpointing data deficiencies and visualising the context of material supply chains (Dalton et al., 2023).

Overall, old bricks can generally be crushed into aggregates for concrete or cleaned and reused for landscaping, road bases, or pavements to contribute to the CE within the building and construction sector. Especially older bricks, where limestone mortar was used instead of concrete, can be easily cleaned and reused as construction materials.

Plasterboard

Plasterboard, also known as drywall or gypsum board, is commonly used to line interior walls and ceilings (Petrone et al., 2016). Plasterboard offers a smooth and even surface for painting or wallpapering, contributing to the aesthetic appeal of indoor spaces. It is an excellent material for partitions, providing a cost-effective and efficient way to divide interior areas (Ferrández-García et al., 2016). Beyond its role in creating walls and ceilings, plasterboard is also utilised for soundproofing (Paul et al., 2015) and thermal insulation (Ariyanayagam et al., 2016), enhancing the overall comfort and efficiency of buildings. Its ease of installation makes it a popular choice for quick and efficient construction processes.

Plasterboard primarily consists of calcium sulphate, occurring in hydrous and non-hydrous forms: dihydrate ($CaSO_4{\cdot}2H_2O$), hemihydrate ($CaSO_4{\cdot}0.5H_2O$) and anhydrate ($CaSO_4$). In contrast to lime and cement-based materials, gypsum board exhibits a neutral pH and is typically white, enhancing its decorative appeal. Gypsum binders are energy-efficient due to lower calcination temperatures (135–180°C) than cement and lime, leading to reduced fuel consumption and minor CO_2 emissions during manufacturing. Despite having low water resistance, the application of chemical admixtures, mineral additions, or the inclusion of cement, lime and reinforcing elements allows for the attainment of diverse properties in gypsum binders (Lushnikova and Dvorkin, 2016).

Plasterboard contributes to the CE in building and construction through various sustainable practices. As a recyclable material, plasterboard supports closed-loop systems, minimising the need for new resources and reducing waste. Its modularity allows for easy disassembly and reassembly, promoting efficient reuse in construction projects (Jiménez Rivero et al., 2016).

Concrete

Concrete is a cornerstone material in building and construction, offering reliability, affordability and adaptability (Asmara, 2024). Concrete is widely used for foundations, pavements and structural elements and provides a solid and reliable foundation (Taylor, 2019). Reinforced concrete supports heavy loads and ensures structural integrity (Gagg, 2014). Further, concrete is frequently used to create walls, columns and beams, forming a skeletal framework of buildings.

Around 30 billion tonnes of concrete is produced yearly, making it the second most widely used material worldwide, surpassed only by water. This prevalence contributes to significant environmental impact, particularly in terms of CO_2 emissions and the depletion of raw materials (Dieter et al., 2022).

As shown in Figure 23, concrete is a composite of cement (12% by weight), water (8% by weight), aggregates (such as sand, gravel, or crushed stone, (around 77% by weight) and sometimes it has admixtures (3% by weight) (VDZ, 2021). Cement is crucial in concrete production, serving as an indispensable binding material. Despite constituting only about 12% of the total weight of concrete, cement manufacturing carries a significant environmental impact. This impact stems from the inherent energy-intensive and carbon dioxide-emitting nature of the cement production process, driven by its distinct physical and chemical characteristics.

Currently, emissions from cement manufacturing contribute to approximately 8% of the global CO_2 emissions (House, 2018). If the cement sector were considered an independent nation, it would emerge as the third-largest emitter of CO_2 globally, trailing behind only China and the United States, releasing a substantial 2.8 billion tonnes of CO_2 (Taylor, 2019). This metaphor highlights the urgent need for sustainable practices and innovations in the cement industry to mitigate its environmental footprint, particularly as more than 70% of GHG emissions in concrete production are linked to cement production (Miller et al., 2016).

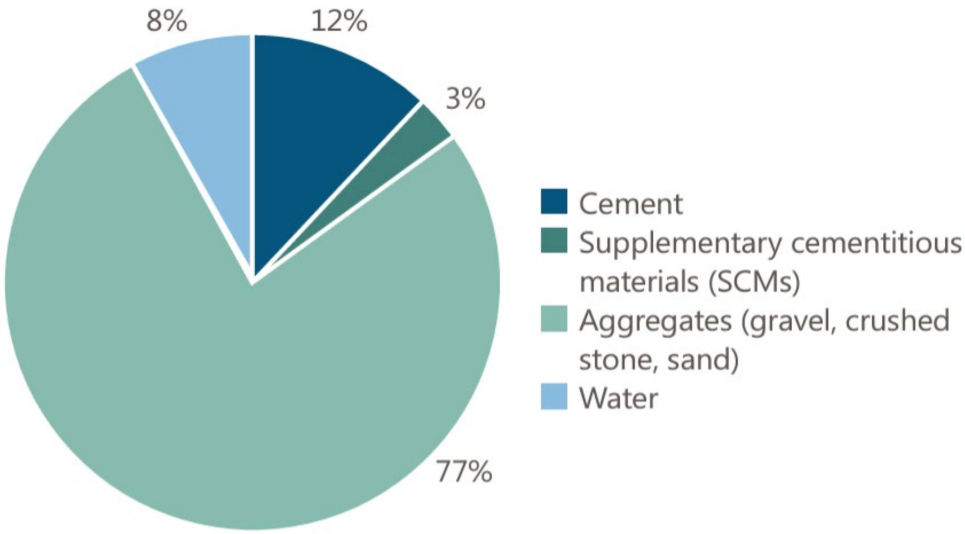


Figure 23. The main constituents of concrete in weight per cent
Source: VDZ (2021)
Copyright 2020 by Cement Industry Federation

Recent studies explore the potential integration of circularity in the concrete industry by incorporating diverse waste materials in concrete production. Findings suggest significant benefits, including cost reduction, lowered energy consumption, decreased carbon and waste reduction through innovative technologies. Despite these advantages, challenges such as mistrust, economic feasibility, market absence, technological limitations, integration issues and a lack of regulations hinder the implementation of a CE in the concrete industry (Adesina, 2022). However, another study (e.g., Miller et al., 2016) revealed that more than 20% of CO_2 emissions could be reduced by implementing (1) heightened utilisation of fly ash and slag, along with increased incorporation of limestone filler (by replacing 20% and 35%, respectively) in cementitious materials; (2) optimal distribution of supplementary cementitious materials, considering that specific strength objectives can be achieved through varying levels of supplementary cementitious material utilisation; and (3) adoption of extended design ages, past the typical 28 days of compressive strength.

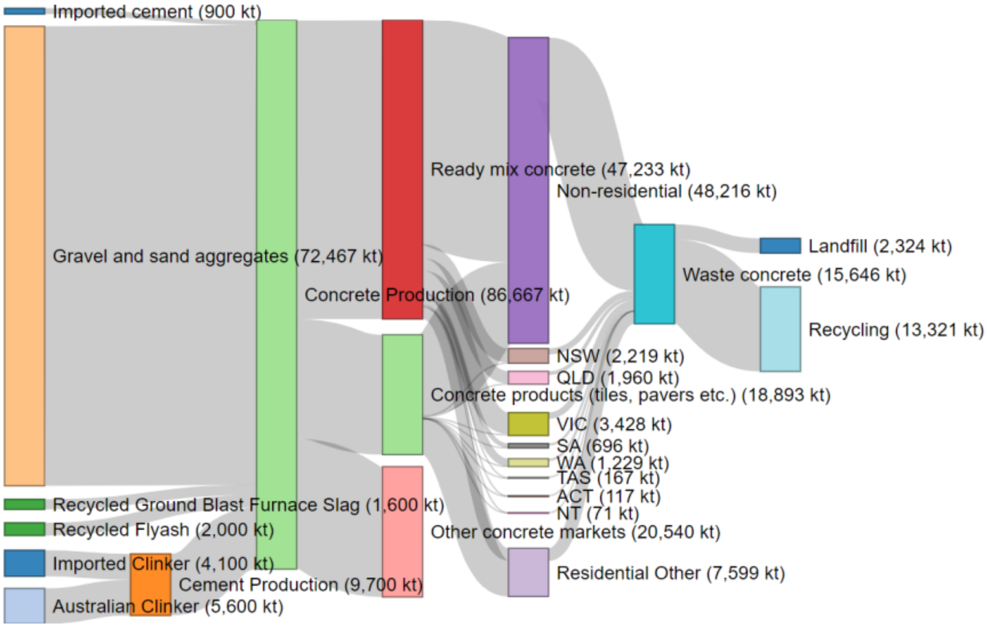


Figure 24. Concrete manufacture, use and waste for detached residential housing in Australia using material flow analysis: 2019
Source: Dalton et al. (2023), CC BY-NC-SA 3.0

Approximately 40% of concrete in Australia is presently allocated to infrastructure projects. Another 30% is dedicated to commercial and non-residential constructions and the remaining 30% is utilised for housing (VDZ, 2021). Within the Australian housing domain, there are two sectors: the Housing Construction Industry (HCI), which is responsible for manufacturing detached houses and the Multi-Unit Apartments and Townhouse Construction Industry (MUATCI), which is dedicated to the production of multi-unit apartments and townhouses (Dalton et al., 2023). Figure 24 shows a material flow analysis conducted for concrete manufacture, use and waste for detached residential housing in Australia in 2019. Almost 85% of the concrete waste was recycled (more than the National recycling rate target of 80%), indicating a positive trend for concrete materials in Australia's CE.

In Australia, a few major integrated enterprises with numerous establishments hold a dominant position in the concrete marketplace. Boral Limited, Hanson Australia, Holcim, Adbri Limited and the Barro Group collectively account for more than 70% of industry sales (Kelly, 2023b). These companies will play a key role in advancing the CE in construction by incorporating recycled content, implementing waste minimisation strategies and investing in concrete waste recycling facilities.

As a versatile and durable material, concrete supports sustainability through its recyclability and potential for reuse. Concrete recycling reduces the demand for virgin materials and minimises waste, contributing to closed-loop systems (Marsh et al., 2022). In addition, the long lifespan of concrete structures reduces the need for frequent replacements, aligning with CE principles (GCCA, 2024). Innovations in concrete technology, such as using recycled aggregates and supplementary cementitious materials, further enhance its eco-friendly profile (VDZ, 2021). Concrete's adaptability to various construction applications, from foundations to pavements, facilitates efficient disassembly and repurposing. By integrating recycled concrete and adopting responsible construction practices, the industry can promote resource efficiency and environmental stewardship in line with CE goals (Marsh et al., 2022). In addition, the durability of concrete structural frames enables buildings to be stripped back to the structure frames during refurbishment and reconstructed for entirely different uses.

Fibre cement sheeting

Fibre cement sheeting is an adaptable building material widely employed in construction for its durability, weather resistance and flexibility. Composed of cement, cellulose fibres and other additives, it is commonly used for external cladding of buildings due to its ability to withstand harsh weather conditions (Hardie, 2003). Fibre cement sheets are also favoured for flooring and roofing and as a base for tiled surfaces, providing a stable and moisture-resistant substrate. Its dimensional stability and resistance to rot and pests make it suitable for interior and exterior use (Innova, 2021).

Fibre cement boards have been employed in construction since the early 1900s. In the 1980s, a significant change occurred when asbestos fibres, known for their health risks, were substituted with alternative fibres, predominantly cellulose fibres. Modern fibre cement boards are now composed of cement, cellulose fibres, synthetic fibres and a mix of additives and admixtures, such as limestone dust, mica, perlite, kaolin and microspheres (Schabowicz et al., 2022).

Fibre cement sheeting supports sustainability through its potential for recyclability and reuse. Fibre cement sheets contribute to closed-loop systems by minimising the demand for new raw materials and reducing waste (Van der Heyden, 2012). Their durability ensures a longer lifespan for building components, reducing the need for frequent replacements and minimising environmental impact. Fibre cement sheeting is often recyclable and can be incorporated into new construction projects, aligning with CE principles. In addition, the material's resistance to environmental factors and versatility in various applications, including cladding and flooring, further enhance its role in sustainable construction practices. Thus, integrating fibre cement sheeting into building projects fosters responsible material use and supports a circular approach to resource management in the construction industry.

Glass

Glass is a multifaceted material that is pivotal in modern building and construction. Its transparency allows for abundant natural light, making it a key component in windows, doors and skylights, contributing to energy efficiency and aesthetic appeal (Dieter et al., 2022). Glass is also utilised in architectural design through curtain walls, creating visually striking and modern building facades. In interior spaces, glass is employed for partitions, balustrades and decorative elements, promoting an open and contemporary feel (Achintha, 2016). Beyond its visual aspects, glass possesses thermal insulation properties and technological advancements have led to the development of energy-efficient glass for sustainable construction (Chen et al., 2023).

The main ingredient in modern glass manufacturing is high-quality silica sand (a non-renewable resource), comprising over 70% of the raw material. Soda ash is added to aid the melting process, while limestone (Boral, 2022) and dolomite are included for durability and weather resistance, as shown in Table 7. These materials are sourced from mining or quarrying, processed and transported before reaching the production line. Glass production is energy-intensive and contributes significantly to global CO_2 emissions, accounting for about 86 million tonnes or roughly 0.3% of total emissions. There are two main sources of CO_2 emissions in glass manufacturing: energy emissions from melting glass, often accomplished by burning natural gas and process emissions from the decomposition of limestone and soda ash during heating (Westbroek et al., 2021). The utilisation of cullet, which refers to recycled glass, is essential for the industry. Its use is crucial in lowering energy consumption and heat-related CO_2 emissions because it requires less energy to melt. In addition, employing cullet helps diminish process emissions by conserving 1.2 times the equivalent amount of raw materials.

Table 7. Raw materials for float glass manufacturing
Source: Arup (2018)

Materials	Glass composition per cent	Reason for adding
Silica sand	72.6	-
Soda ash	13.0	Easier melting
Limestone	8.4	Durability
Dolomite	4.0	Working and weathering properties
Alumina	1.0	-
Others	1.0	-

Figure 25 illustrates the global glass map, depicting the journey of glass from raw materials to its end-of-life stage. The width of each pathway represents its mass, with values given in Mt. The glass life cycle commences on the left side of the diagram with the preparation of 144 Mt of virgin raw materials and 28 Mt of cullet. These materials are melted in the furnace, yielding intermediate products of flat glass (96 Mt) and container products (97 Mt), as well as the release of process emissions (22 Mt) due to the decomposition of virgin feedstock. Intermediate production undergoes reworking, cutting and quality checks, resulting in fabricated flat products (71 Mt), container products (79 Mt) and an internally recycled cullet. Final products, including those predominantly used in buildings (59% flat glass), could be either recycled or disposed of in landfills when they reach end-of-life. However, end-of-life flat glass cullet availability has been constrained for years (Westbroek et al., 2021).

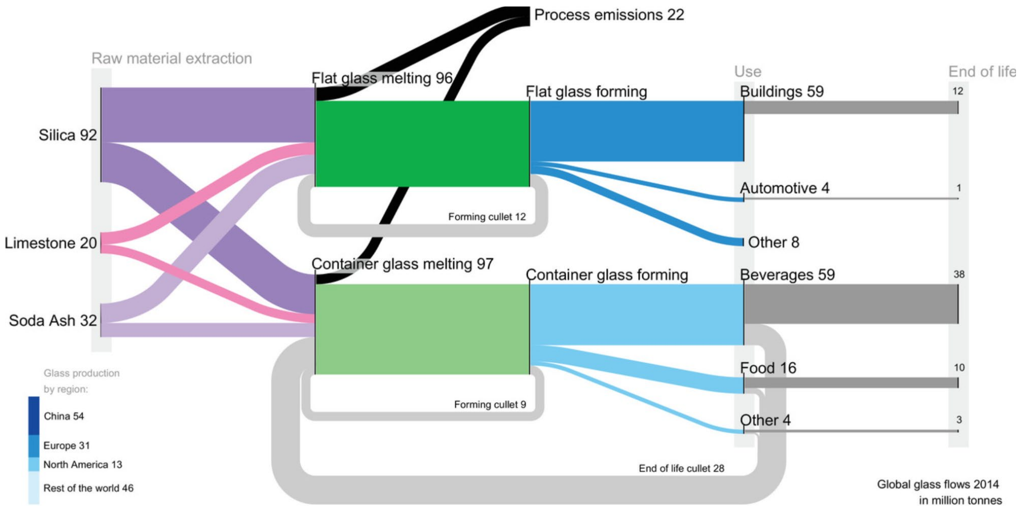


Figure 25. Global flows of glass in 2014, from raw materials to end of life (the width of the lines is proportional to the mass of flows)
Source: Westbroek et al. (2021), CC BY 4.0

End-of-life building glass is generally not recycled into new glass products. Instead, it is often crushed with other building materials and put into landfills or recovered with other C&D waste as facilitated by its inert characteristics. It currently has a low market value because it lacks properly organised collection and recycling systems to generate what could become a valuable glass-making raw material (Glass for Europe, 2020).

However, the lifespan of flat glass in buildings is assumed to be 75 years (Westbroek et al., 2021). Hence, the durability and longevity of glass in construction components contribute to sustainable practices by extending the life cycle of building materials. In addition, innovations in glass technology, such as energy-efficient and low-emissivity glass, enhance its eco-friendly profile. The industry can move towards more environmentally friendly solutions by incorporating recycled glass and adopting responsible construction practices (VDMA, 2020). Nonetheless, inclusions in glass to improve its thermal or light transmission performance can impede its recyclability.

Composite materials

Composite materials offer a versatile and innovative solution combining different materials to enhance performance and properties. These materials typically consist of two or more components, such as fibres, resins and additives (American Composites Manufacturers Association, 2024). These component materials possess distinct chemical or physical characteristics and are combined to form a material with discrete properties from their individual elements. These properties maintain their separate identities and set composites apart from mixtures and solid solutions (Yao et al., 2019).

In construction, common engineered composite materials encompass reinforced structures like concrete and masonry, composite wood types such as plywood, strengthened plastics like fibre-reinforced polymer or fibreglass, ceramic matrix composites combining ceramic and metal matrices and metal matrix composites. Various advanced composite materials are also employed (Yao et al., 2019). They are known for their high strength-to-weight ratio, corrosion resistance and durability, making them suitable for diverse environments. Composite materials enable creative design possibilities due to their ability to be moulded into complex shapes (Aerovac, 2024). Their adaptability, lightweight and resistance to environmental factors contribute to sustainable construction practices. Furthermore, there is a growing interest in composite materials sourced from animals and natural sources due to the advantages of minimising their carbon footprint.

However, composite materials are difficult to recycle due to their heterogeneous hybrid structure. Mechanical, thermal and chemical methods could be applied to recover certain types of materials (Yang et al., 2012). However, their durability and resistance to corrosion make composites suitable for long-lasting structural components, promoting resource efficiency by extending the life cycle of building materials. Moreover, the adaptability of composites allows for innovative design solutions and modular practices, facilitating efficient disassembly and reassembly (Greenwood, 2024).

Alternative Bio-based Materials

Bio-based materials may be wholly or partially derived from renewable resources, by-products and/or biowaste of plant or animal biomass, which are generally turned into insulation materials (concrete, filler or binder for concrete or mortar and materials for indoor applications such as creating flooring and ceilings (Le et al., 2023; Mouton et al., 2023). Challenges may include finding options that equate to the principal advantages of traditional materials, including tensile strength, which is why Australia's building codes and standards may not currently support the implementation of some of these newer building materials. Further, there may be a lack of availability of bio-based materials at a commercial scale and depending on the bio-based material, the environmental performance can be worse than conventional materials, such as installing cork insulation board compared with commonly used polystyrene (Sierra-Perez et al., 2016). Therefore, there is a need to investigate the capacity of each material, its characteristics and environmental impact on a case-by-case basis.

While mitigating negative health and environmental impacts is a strong motivator for replacing traditional materials with safer bio-based alternatives, barriers remain.

Rigorous research demonstrates that the benefits of using bio-based materials can substantially lower carbon emissions and reduce waste and consumption of fossil fuels (Rabbat et al., 2022). Bio-based materials can also be more efficient in terms of operational energy consumption. Trends are emerging for developing various kinds of eco-concrete, which deserve attention for wider adoption as these technologies become commercially available, including algae-based concrete, a low-carbon cement-like material that sequesters and stores carbon.

Bio-based materials not only offer healthier options but may also be more economical than conventional ones. For instance, coconut shell concrete has cheaper production costs than traditional concrete (Azunna et al., 2019). Rice husk ash concrete and wood powder used instead of sand in cement mortar are cheaper (Ince et al., 2021) and straw bale houses are less expensive than conventional ones (Mutani et al., 2020).

Importantly, some of these bio-based materials are not new. Rather, they were used prior to the introduction of synthetics and have withstood the test of time. They are even considered conventional in nature, including previously discussed materials such as wood, stone, clay, or mud brick. Meanwhile, other bio-based materials that are less employed may be experiencing a resurgence correlated with the popularity of sustainable building practices.

When conditions are appropriate to apply these options, the following bio-based building materials should be considered. The key to these builds is obtaining adequate supplies and finding skilled workers to carry out the specialised construction.

Rammed earth

Rammed earth is a popular primary raw material for construction found in Neolithic archaeological sites, dating as far back as the 5th millennium BC (Tang et al., 2022). It can be applied in various climatic conditions because rammed earth helps regulate thermal transfer and humidity (Ávila et al., 2021).

Rammed earth buildings require less energy—up to 48% less for heating and 84% less for cooling (Environmental Valuation, 2020)—making for comfortable surroundings (Ben-Alon et al., 2020). These houses appear to blend into their settings (Manso et al., 2021). Increasingly, people add green roofs and walls to these structures, allowing greater opportunities to live harmoniously among nature. Green roofs and walls are designed to hold soil and growing medium to support plants (YourHome, n.d.).

Figure 26 shows that rammed earth walls are composed of aggregates—sand, silt, clay and gravel—moulded between flat panels with a mechanical ram. Although similar to the appearance, use and performance of adobe blocks, rammed earth blocks differ in technique. They do not require water to be added to the mixture (Obonyo et al., 2010). However, cement is added today to enhance structural strength and durability and the walls are built in layers rather than stacking blocks on top of one another.

Figure 26. Rammed earth walls
Source: Libby Haslam (2006)

These houses are usually built partially underground, with one side cut out into the slope of a hill (March, 2024). During construction, the earth is placed into a section of wall with a rammer. An air compressor is used and a wall layer is tamped down to at least 15 cm thick. Each layer does not need to be fully dried or cured while building, but it is important to prevent moisture from setting in. Bonding or collar beams with reinforced rods need to be placed in the walls for structural support (Hu, 2023).

Finished internal walls are generally 200 mm to 300 mm thick. External walls can be up to 300 mm thick and an air-permeable sealer can extend the material's lifespan and structural stability (YourHome, n.d.). Rammed earth sites must be maintained and it is critical to keep them well-drained and protected from heavy rainfall (Hu, 2023).

There are no cavities in rammed earth walls to attract and support pests. Hence, the monolithic mass is beneficial to insulate against sound. In addition, earth-sheltered housing provides a potential solution for people living in bushfire-prone areas because buildings can be designed for bushfire resistance. Glass is a key component of these structures, with windows that must be adapted to high thermal pressure because glass is susceptible to heat. Although sustainable, the enhanced reinforcement substantially increases expenses for specialised engineering, excavation, concrete padding and construction, averaging AUD 53,000 to AUD 273,000 above a normal dwelling (Yarra Ranges Council, 2024).

Typically, one side of a rammed-earth building contains larger windows to permit sufficient natural light to penetrate the interior. This side is generally oriented downhill towards the landscape, while the rear of the building will be carved into the slope of the hill. Since bushfires tend to escalate in speed and intensity when spreading up a hill, the outlook side usually bears the brunt of a bushfire attack (March, 2024).

A rammed earth house can be engineered for a lower chance of destruction, but other risks may need to be considered. Cutting into the hillside can make houses vulnerable to landslides. Further, people might plant vegetation, store gas bottles, fuel and other flammables that counteract bushfire protection, or forget to secure their windows or doors. While interest in underground dwellings has grown in Southeast Australia since the Black Summer bushfires of 2019-20, earth-covered housing is only be one solution in a suite of tools. Living in housing farther from disaster-prone zones is considered a safer alternative (March, 2024).

Hemp masonry

Hemp is widely grown across Australia for food or industrial purposes. The majority of commercial production is in Tasmania (Victoria Government, 2020). Hemp masonry or hempcrete is a composite of the inner fibres of hemp hurd. It is mixed with water and lime binder (sand is optional). Hempcrete has become highly sought after for fibreboard, insulation, cement, stucco and mortar, or as a fibreglass substitute (Ooyen, 2019).

Hempcrete does have other benefits. It is a good insulator and a vapour-permeable material that provides comfort and good air quality in a building. Formwork as form ply is widely available and hempcrete mixture can be sprayed or poured into formwork and tamped down to bind walls, facilitating their fabrication on site. Also, a timber frame can be embedded for structural strength in conformance with NCC requirements and Australian Standard AS 1684 Residential timber-framed construction (SAI Global, 2006). External walls should be rendered for water protection and if internal walls are left ‘off form’, i.e., without render, an air-permeable sealer is recommended (YourHome, n.d.). Zampori et al. (2013) demonstrated that incorporating hemp-based insulation in building panels, compared to conventional rockwool, enhances the sustainability performance of walls with similar thermal properties by reducing cumulative energy demand and global greenhouse gas potential.

Figure 27. Highland Hemp House
Source: Tommy Gibbons (2018)

In addition, hempcrete offers good acoustic insulation and a proper building envelope will be pest-free and fire-resistant. While there is zero toxicity in a finished build, facilitating good air quality, ventilation is a critical component of a hempcrete structure (see all the windows in Figure 27). Post-consumption, a hempcrete wall can be deconstructed, allowing timber reuse and hemp reuse or composting (YourHome, n.d.).

Straw bale

Straw bale is a secondary natural material used in construction (Hu, 2023). A by-product of mature plants, straw bale comes from wheat, barley, oats, rice, corn and other types of agricultural stalks of plants once they have been harvested (Onyegiri & Ugochukwu, 2016). This type of building dates to the Palaeolithic era. Historians assume the dry part of a straw plant was used by early settlers in places where trees were limited and soil made a sod type of housing impractical (Koh & Kraniotis, 2020).

During construction, a mechanical baler is used to fix each bale together. The shape, dimension and amount of compression depend on the machine and crop. Barley bale density varies from 54.6 kg/m^3 to 78.3 kg/ m^3, while wheat and oat bales range from 81 kg/ m^3 to 106.3 kg/ m^3 (Tlaiji et al., 2022). Rice straw alternatively has a high amount of silica, which makes it denser and more resistant to decomposition (YourHome, n.d.).

Straw bale is a versatile material. It is often used for thatch roofing or combined with earth to make cob, wattle, or daub walls (YourHome, n.d.). When pressed into Durra panels, straw can replace internally framed walls and plasterboard (Light House Architecture and Science, 2023). These panels have been approved as an FM-approved Class 1 construction material and offer good fire resistance. Most straw bale construction incorporates steel or timber framing to ensure it is structurally sound and complies with the NCC (Figure 28). If straw is protected from moisture, it will be durable. Thus, it is advisable to make the walls waterproof but breathable. By densely packing and protecting the bales, the walls will be pest-free and have good sound insulation properties. Although the thermal conductivity of straw bale construction is less than that of wood, brick and concrete, its specific heat capacity approximates traditional materials at 1075 to 2000 J/(kg K). Evidence indicates straw bales are adequate to build high-performance exterior loadbearing walls due to their hygrothermal performance and thermal capacity, but in modern times, they are usually used for the building core, such as insulation. It is important to make sure to insulate all the windows and roofing to maintain the overall performance of the building (Marques et al., 2020). Once framed, a render is overlaid on the bales, lending extra thermal mass to the skin of a building. An earthen render that may incorporate a bit of lime is the best choice compared with cement, lime and sand, or lime putty and sand because an earth render will minimise environmental impact, save time in preparation and application and reduce the embodied energy of the building (YourHome, n.d.).

Straw is an environmentally friendly material because it significantly reduces the non-renewable resources needed to manufacture materials. Using straw in buildings can also reduce air pollution and store carbon. Post-consumption, the straw will decompose in the soil for mulch use (YourHome, n.d.). However, unless produced locally, the cost of transportation can also be high due to the low density of straw bales.

Figure 28. Straw bale house
Source: Hayley Green (2009)

Although straw is inexpensive and readily available, construction is labour-intensive and requires specialised building knowledge. Therefore, it is advisable to hire an expert and recruit volunteers who want to learn this skill before embarking on straw bale construction. Ausbale (2024) is building industry professionals, owners, researchers and interested citizens willing to share their knowledge and experience of straw bale building.

Market review

This market review focuses on practical examples within the Australian context, examining key areas such as education, certification and investment in the CE. By analysing current trends and initiatives, the review provides an overview of how Australian construction stakeholders are adapting to and integrating CE principles.

The market review highlights the role of educational programs in fostering a skilled workforce, certification in ensuring compliance and best practices and the impact of investment in driving innovation and CE development across businesses.

Education and training

Teaching about sustainability and circular building practices reflects divergent approaches by providers. Within higher education, these topics need to be embedded by building a business case to mobilise greater resources and institutional support (Ogunmakinde, 2024). While it is not mainstream yet, many universities have started offering sustainability or circular curricula in architecture and design and engineering faculties. Table 8 provides information about selected offerings of Australian universities.

Professional bodies around the country, such as Engineers Australia, schedule continuing professional development events on related topics for their members. They offer conferences and networking events, courses and programs as well as micro-credentials. However, the number of courses that centre around the CE and sustainability are limited.

Table 8. Selected courses on Sustainable Architecture offered by Australian Universities
Source: Own elaboration

Higher Education Institution	Course	Comments
University of Sydney	Master of Architectural Science (Sustainable Design)	Industry-focused, sustainable buildings, including construction technologies, energy analysis, lighting innovation and integration of urban ecologies
University of Melbourne	Master of Architecture	Use of new materials and technologies to create environmentally sustainable buildings
University of New South Wales	Bachelor of Architectural Studies Master of Architecture	Architectural design, including sustainability, environmental impact and use of sustainable materials Emphasis on sustainable design principles and environmentally responsible buildings
RMIT University	Master of Energy Efficient and Sustainable Building Advanced Diploma of Building Design (Architectural) Graduate Diploma in Energy Efficient and Sustainable Building	Sustainable building design, building energy and climate engineering, management of sustainable building projects Vocational course – sustainable design for domestic and commercial-scale building projects Science, design technologies and management of sustainable buildings
Queensland University of Technology	Master of Architecture	Focus on sustainable systems and the application of advanced digital tools to address sustainability
University of Queensland	Bachelor of Architectural Design Master of Architecture	Emphasis on sustainable architectural practices
University of Technology Sydney	Master of Architecture	Sustainable design principles, emphasis on sustainability, environmental impact and sustainable materials
Monash University	Master of Architecture	Focus on social and spatial justice, environmental sustainability, thriving communities

Several local organisations, like the Adelaide Sustainable Building Network (ASBN) and Conservation Council ACT, host events and email newsletters to disseminate information about sustainable industry practices. These manifestations of CE practices, dubbed ‘living laboratories’, can be powerful mechanisms to cultivate sustainable behaviours (Gomez & Derr, 2021). The events are open to interested members of the industry and the public.

Developing hands-on skills and training for types of sustainable building practices may be obtained through a vocational institute. For example, the Box Hill Institute of TAFE offers Passive House short courses to teach people the methodology to design and construct thermally efficient buildings. Besides gaining apparent career benefits, such knowledge and skills are also expected to raise the qualifications and employability of graduates (Nikoloudakis & Rangoussi, 2024). Online education providers and industry practitioners also offer their training, particularly in designing energy-efficient houses.

The **Circular Economy Research Network of the Asia-Pacific (CERN-APac)**, established in 2022, held its inaugural conference in November 2023, featuring well-known sustainability experts in Australia. The 2023 conference brought together researchers, industry, community and government representatives to plan how research can help address prioritised CE challenges. The group focuses on capability building and research development in the CE and one of their twelve sectors is the construction and building industry.

The Australian Circular Economy Hub's webpage provides valuable information about the CE in general and lists the built environment as one of the industries under their knowledge hub category. They provide research reports, articles, videos and case studies to inform about the CE. The hub also recognises the importance of education and training but states that for the business community currently only a limited number of specialised training programs are available. In addition, they will list CE programs from universities and TAFEs when they become available (Australian Circular Economy [ACE] Hub, 2024).

The main barriers to implementation of a CE are lack of legislation, lack of knowledge among designers of environmental benefits, lack of techniques to execute it, and the small relative size of the market would also limit economies of scale (Ipsen et al., 2021; Ogunmakinde, 2024). Junior et al. (2020) recommend assembling appropriate governance to promote sustainable development through policies that would facilitate the adoption of practices for waste management, energy efficiency and circular procurement. Drawing from best practices of different contexts can allow students to identify the most suitable strategies for specific circumstances and help them build a case to implement a CE within institutions.

Certification schemes for sustainability and reporting

There are many certification schemes that rate energy and water systems and other sustainability criteria for new and major refurbishments of individual buildings, entire project sites, or real estate and infrastructure investments for reporting and decision-making. The **Building Research Establishment Environmental Assessment Methodology (BREEAM)** was the first method introduced in 1990 to assess, rate and certify buildings overall. Systems have now expanded to assess water, waste, energy, transport, biodiversity and social standards.

Measurements of circularity for products and materials that go into buildings or the manufacturing of products are included in the **Material Circularity Indicator (MCI)** and the **Research Conservative Manufacturing (ResCoM)** platform, which concern reducing waste and protecting the environment (World Green Building Council, 2024b). As presented in Table 9, there are additional independently operated national and global rating tools. Each scheme is structured differently and has different categories and prerequisites to earn credit points towards varying levels of certification, including **Green Star**, the **Global Real Estate Sustainability Benchmark (GRESB)** and the **Leadership in Energy and Environmental Design (LEED)**.

Table 9. Various national and international building tools and their purposes
Source: Own elaboration

Rating tools	Global, national or local	Focus of indicators
BREEAM	Global	Energy Efficiency
LEED	Global	Environmental and Social Performance
MCI	Global	Circularity of products and materials
ResCoM	Global	Circularity of product systems
GRESB	Global	ESG benchmark of real estate and infrastructure assets
Green Star	Australia	Health and environmental responsibility
NatHERS	Australia	Energy Efficiency of Homes
NABERS	Australia & UK	Environmental Performance of Buildings and Tenancies

For example, LEED is recognised worldwide as a hallmark of excellence in building performance because of its stringent requirements to demonstrate best practices in site waste management, energy performance, hydro-savings, installation of energy metres and minimum air renewal rates (Suzer, 2019). It also rewards buildings that take a life cycle approach, i.e., it prioritises local manufacturers, selection of natural, non-toxic materials and recovery of demolition materials. Its categories are depicted in Figure 29 (US Green Building Council, n.d.). Established industry tools are constantly evolving while new ones are being generated. Building certification systems, WELL and Fitwel, have started to focus on the health and wellness of building occupants.

Figure 29. LEED certification has eight conditions for assessment
Source: Adapted from US Green Building Council (n.d.)

In recognition of the risks of climate change, measuring and reporting on environmental, social and governance factors has become a critical part of investment decision-making. The **Task Force on Climate-related Financial Disclosures** (TCFD, 2024) is one framework that global organisations use to evaluate property investment risks and determine how to choose future-proofed assets. Nearly two-thirds of ASX200 companies have committed to or voluntarily report climate-related information against the TCFD framework. Climate disclosure will become mandatory in the next few years for large entities, such as the **National Greenhouse and Energy Reporting (NGER)** reporters and asset owners (Treasury, 2024). **The Australian Accounting Standards Board** is drafting standards based on those issued by the **International Sustainability Standards Board (ISSB)**.

Green lending and investment

In response to the demand to act transparently and tackle material-related risks, newer sustainable investment opportunities, known as green finance, are emerging. These investments can be socially inclusive as well as environmentally responsible. They target abatement in GHG and encourage broad activities of climate change mitigation and adaptation (Noh, 2019). Besides finance, these activities include overseeing operation and risk management in projects to offer protection of assets and cleaner energy at lower cost and deliver greener buildings and transport (EIB & GFC, 2017). Green finance remains relatively immature despite its promise of bringing better building practices.

Strengthening economic returns, clarifying regulations and creating more awareness of green finance can drive its acceptance and evolution.

However, contradictions over what constitutes green finance need to be addressed. It is important to continue to spread awareness of the potential advantages of green finance so that successful us can be leveraged to make more green finance available. Then, financial institutions will likely issue more credits, subsidies and lower interest rates for developers who build green facilities (Akomea-Frimpong et al., 2022).

Australian green investment types

Australia has a gradually growing pool of green infrastructure and building investments that support a transition to a low-carbon and climate-resilient economy. These initiatives contribute to delivering lower-carbon transport, renewable energy, improved water management and green buildings. Institutional investors, represented by superannuation funds, corporations, property companies, banks and government, are seeking long-term growth in projects and assets for project owners and developers that can deliver water, energy and waste benefits to contribute to sustainable cities and states across the Asia-Pacific region (Climate Bonds Initiative, 2018).

Dedicated financial products include green loans and bonds, social and sustainable bonds, green infrastructure investment trusts and clean energy funds, ETFs and socially responsible funds, complemented by public and private equity investments (Taghizadeh-Hesary et al., 2021). One popular type of financing, green bonds, is a debt instrument for exposure to green projects and assets. They are administered to finance transformation for companies holding high carbon or energy-inefficient portfolios.

To be eligible to unlock capital investment for retrofitting and/or retro-commissioning to undertake improvements, rating tools and benchmarking frameworks are used to demonstrate compliance with built environment projects and assets. For instance, a commercial building would need to qualify for a NABERS rating.

Recently, the Australian Government released a **Green Bond Framework** that specifies its climate change and environmental priorities and identifies how green bonds will finance eligible expenditures. The Government also announced an inaugural $7 billion sovereign green bond program aiming to boost the scale and credibility of Australia's green finance market through greater transparency of climate outcomes and making investments available that will attract more multinational and private sector finance. Initial financing will be put towards financing the Sydney Metro and Rewiring the Nation - a $20 billion program for establishing renewable energy zones for cities to transition to net zero. It was accomplished by engaging investors from the initial design concept through its issuance of debt (Australian Financial Review, 2024).

Table 10 lists green credit in loans that are available for the residential and commercial sectors in Australia. Other opportunities lie in directing investment in green mortgages, especially for renovations or developing affordable, sustainable and resilient homes as costs soar. These instruments will reduce living costs and thereby reduce mortgage risk default. Commercial funding is particularly robust and plays an increasingly leading role in supporting green building, energy efficiency, renewable energy, clean transportation, waste management and climate change adaptation (Armour et al., 2023).

Table 10. Australian Green Investment Loans
Source: Own elaboration

Schemes	Organisations	Targets	Funding amounts or repayment rates
Green loan	CBA	Renewables	Up to $20,000
Green loan	Bank Australia	Clean energy	Reduced variable home loan rate for five years or fixed rate for three years with a Clean Energy Home loan
Green loan	loans.com.au	Solar power	5.99% per annum
Green loan	Westpac	Solar & battery	$4,000 - $50,000
Green, social and sustainability loans	NAB	Clean energy, ESG	$5,000 - $55,000
Green loan	NAB	Energy efficiency and environmentally-friendly buildings	TBD
Australian Recycling Investment Fund	Clean Energy Finance Corporation (CEFC)	Renewable energy, energy efficiency and low emissions technologies	$10,000 - $5M
Green loan	Sustainable Australia Fund	Energy efficiency – renewable energy & battery storage, insulation & electric vehicle charging stations	Up to $200,000 for businesses

The Australian Government has numerous assets held by local, national and global funds, ranging from regulated water and sewage utilities, distribution and transmission pipelines and user-fee assets, including toll roads, airports, ports and railways and commercial operations from communications to power generation and energy providers (McInerney et al., 2019). Establishing a robust green finance market could result in increased capital and expertise invested in more green assets to realise enhanced national development.

Moreover, green treasury bonds are significant. They set a risk-free rate of return that flows to all forms of green finance. Households and businesses can then access finance to accelerate change. Policy interventions to support additional growth of green finance with carbon markets, in addition to investment opportunities, including the **Nature Repair Market Act** (DCCEEW, 2024d), would accelerate this transition.

If Australia intends to reach its climate targets and extend economic and social well-being, the government cannot achieve this capability without tapping into diverse funding mechanisms. These could include foreign direct investments and superannuation funds, as well as continuing to partner with financial managers who have a strong global presence in infrastructure, debt financing and alternative assets to drive better value-for-money outcomes (Australian Financial Review, 2024).

Insurance and risk management

Australia's insurance industry is dominated by large national companies. These companies are strongly connected to policy debate and decision-making at nationwide spatial scales (Dolk & Penning-Rowsell, 2020), particularly after flooding and other natural disasters that cause rebuilding or replacement.

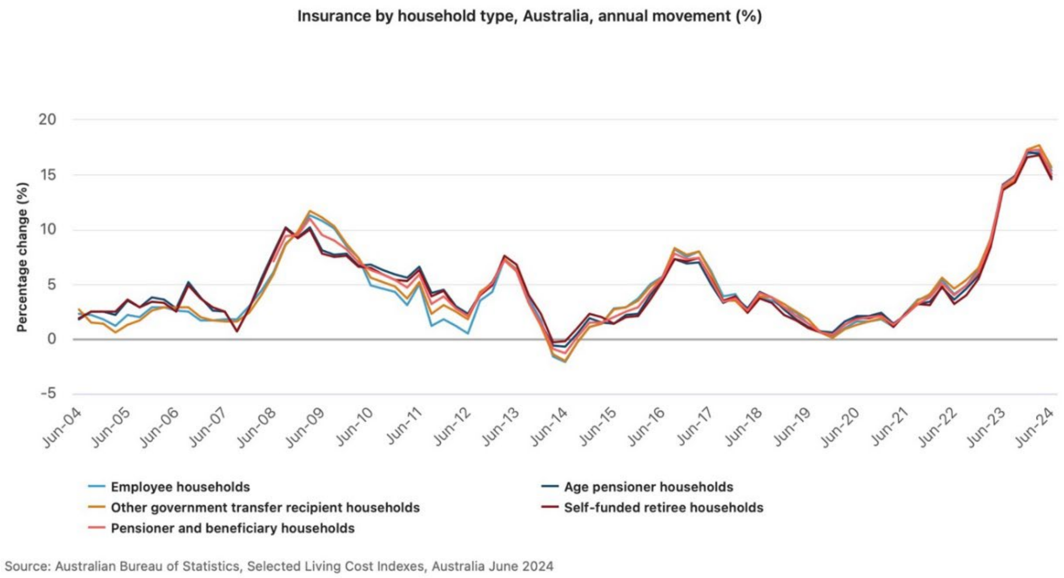


Figure 30. Surge in Australian insurance prices,
Source: Australian Bureau of Statistics (2024),CC BY 4.0

While insurers are supposed to protect consumers against financial harm in the event of property destruction, the availability and affordability of private insurance coverage in at-risk localities have become a hotly contested issue. As demonstrated in Figure 30, insurance bills for Australian households have spiked since 2022 (Australian Bureau of Statistics, 2024).

The acceleration of weather-related events has made Australian buildings and infrastructure increasingly vulnerable to disasters and led to higher property insurance rates. Despite post-disaster national inquiries by the government, calls to invest in pre-disaster mitigation strategies to ensure citizens receive and can afford adequate protection and strengthen their well-being and property resilience have lagged (de Vet et al., 2019).

Premium and educational incentives

A study on the impact of green buildings on loans in the commercial mortgage-backed securities market found that green buildings not only translate into less risk but a model and matched-sample analysis demonstrated that green buildings also have a 34% lower risk of default due to their favourable loan-to-value ratio precisely because risk has been decreased by a better price premium (An & Pivo, 2020). Loans on green buildings secure somewhat better terms. While the difference is edging upwards, the effect is economically small compared with the risk of default.

Despite the availability of these measures, householders largely do not benefit from the intended relief. While insurers at times increase flood coverage in standard home and contents insurance policies, there has been a historic reluctance by the government to impose interventions through subsidisation (Dolk & Penning-Rowsell, 2020) to assist with costs of mitigation and sharing risks across regions experiencing variable exposure to harm. The Productivity Commission Inquiry into Regulatory and Policy Barriers to Effective Climate Change Adaptation, set up in September 2011, recommended that *'governments should not subsidise household or business property insurance, whether directly or by underwriting risks'* (Productivity Commission, 2012, p. 31). It argued that *'poorly designed regulatory intervention in insurance markets can create barriers to effective adaptation to climate change'* (Productivity Commission, 2012, p. 315) because subsidisation could deter risk management.

There is contrary evidence, though, that household insurance provides a pathway to preparedness and resilience, such as when insurers factor retrofitting technologies into the pricing of policyholders to extend the coverage of people who can make changes to their homes (de Vet et al., 2019). Insurers and the government appear reluctant to implement major changes addressing building protection issues, often entangled in policy debates during major disaster events (Dolk & Penning-Rowsell, 2020). Post-disaster response and recovery remain the industry norm.

Nonetheless, there has been a slight shift in premiums. The Australian Government, National Emergency Management Agency (2023), recently decided to contribute funding to the **Resilient Building Council (RBC)**. The Council released an app that helps homeowners prepare for bushfire risks. It has been endorsed by large insurers, NRMA and Suncorp, to lower insurance premiums up to $500 for homeowners that assess site-specific bushfire risks of three stars or higher and demonstrate retrofitting has been taken to curtail these risks. In a trial, a 67% improvement was calculated for 1,200 households participating in the app's co-design. NAB has joined those insurers by giving an interest rate cut to its customers who are homeowners that live in Shoalhaven, NSW, which was severely impacted by the Black Summer bushfires of 2019-2020 (Australian Government, National Emergency Management Agency, 2024).

In addition, insurance agencies run extensive educational campaigns in person and online to prepare communities to take more proactive steps to safeguard consumers and their properties in a shift towards shared responsibility between the government and insurers (Eriksen et al., 2020). The RBC is also planning to enlarge its rating program with an invitation to give on-site assessments to homeowners to help them prepare an integrated and comprehensive resilience strategy by examining their exposure to cyclones, bushfires, flooding and heatwaves and measuring their energy efficiency (Australian Government, National Emergency Management Agency, 2023). Therefore, the Government also plays a crucial role in advancing the CE within Australia's building industry by creating policies and legislation to support circularity.

Findings from workshops, interviews and case studies

This section reports the findings of the co-design workshops, interviews and site visits conducted for this scoping study to investigate the current CE perspectives and initiatives of various stakeholders in the construction industry across the value chain, including key strategies, enablers and barriers. The findings span Australia and provide insights from different states and local contexts, as well as global examples and best practices.

Transition to a circular economy

The CE in Australia is characterised by an **early stage of adoption** and the transition to a CE in the construction industry is currently unfolding. Findings show that outstanding examples of Green Star rated buildings and precincts exist already, but CE adoption in Australia is fragmentary. Several workshop participants had never heard about the concept of the CE prior to the workshop and many companies struggle to integrate the CE into their business strategy. Nevertheless, many significant initiatives were presented during the study, signalling progress on the horizon, particularly in the perspectives on construction materials and C&D waste. Activities are in place to reduce or prevent waste and pollution and to revalue and extend the life cycle of materials. Moreover, there is a growing momentum to incorporate pathways for achieving better social outcomes and researchers found an appetite to extend circular opportunities among industry, government and academia to implement solutions. Although opportunities are unfolding, they are neither rapid nor at the scale to satisfy industry demands.

As defined by the ISO (2024), ***circularity*** refers to **the degree of alignment with the principles for a CE**. ISO 59020:2024 mandates how CE is measured and circularity performance is assessed. It defines **core circularity indicators** relating to resource inflow, resource outflows, energy, water and economics. However, only resource inflow and outflow indicators are mandatory, i.e., only indicators that relate to material use. However, achieving high material circularity indicators is very challenging as illustrated in Figure 31.

The graph depicts the development of the material circularity indicator based on the assumption that 20 Mt of recovered material is available for use in building projects, i.e., approximately the amount that is currently available. In 2019, approximately 250 Mt of virgin materials were used for housing, i.e., the value used in the graph. Subsequently, the material circularity indicator is calculated while reducing the amount of virgin material but assuming 20 Mt recovered material is available (Miatto et al., 2024). The figure shows that the amount of virgin material must decrease substantially (i.e., by 190 Mt, from 250 Mt to 60 Mt) for the material circularity index to reach 25%. However, the graph does not consider the reduction of mining wastes when recycled steel and aluminium are used which would lead to a reduced consumption of virgin materials.

Although a conscious use of material is important in establishing a CE, the focus cannot just be on material use and recycling. Importantly, there should be a focus on other non-material CE principles, such as regeneration and pollution. Non-renewable and renewable materials need to be used in smarter ways to create more sustainable impact.

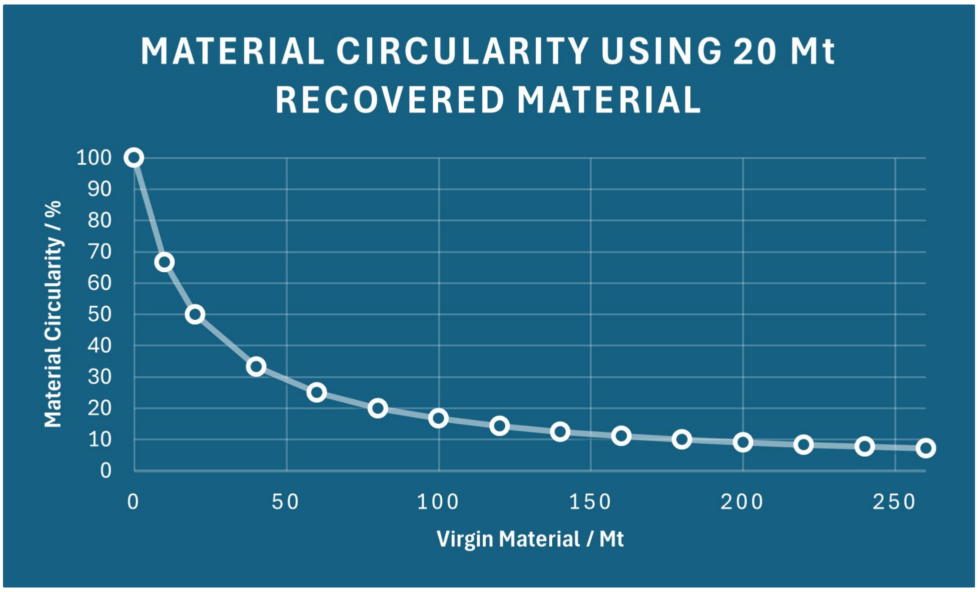


Figure 31. Development of the material circularity indicator by reducing the amount of virgin material (Mt) used and keeping the amount of recovered material at 20 Mt.
The amount of virgin material must be reduced significantly for the circularity indicator to rise above a value of 25%.
Source: Own elaboration

New business models need to be established that not only focus on designing-out waste but also overconsumption and that are more aligned with nature and address regeneration while contributing to social wellbeing.

Cramer (2022) evaluated the CE policies and practices for several selected countries and regions between 2020-2021 (Figure 32). According to a group of indicators selected, Australia scored relatively low on the CE readiness state. In contrast, some European countries are at the forefront of CE progress.

Indicators for Circularity

		National policy plan[2]	Landfill percent[1]	Incineration percent[1]	Recycling percent[1]	Product policy[2]	Second hand[2]	Repair[2]
1	Netherlands	Yes	Low	High	High	Yes	Medium	Medium
2	Flanders	Yes	Low	Medium	High	Yes	Medium	Medium
3	Italy	No	Medium	Medium	Medium	Yes	Medium	Low
4	Finland	Yes	Low	High	Medium	Yes	Low	Low
5	Norway	Yes	Low	High	Medium	No	Medium	Low
6	Scotland	Yes	Medium	Medium	Medium	No	Low	Low
7	Hungary	No	High	Medium	Low	No	Medium	Low
8	Slovenia	No	Medium	Medium	High	No	Low, but growing	Low, but growing
9	Slovakia	No	High	Low	Low	No	Low, but growing	Low, but growing
10	Czech Republic	No	High	Medium	Low	No	Low, but growing	Medium, but growing
11	Poland	No	High	Medium	Low	No	Low, but growing	Low
12	Taiwan	Yes	Low	Medium	High	No	High	High
13	Turkey	No	High	Low	Very low	No	Low, but growing	Medium
14	Australia	No	High	Low	Medium	No	Low, but growing	Low
15	Brazil	No	High	Low	Low	No	Low, but growing	Low, but growing
16	Canada	No	High	Low	Very low	No	Low	Low

Note: Landfill: low (<8%), medium (8-38%), high (>38%); Incineration (conventional and energy recovery from waste): low (<11%), medium (11-41%), high (>41%); Recycling municipal waste: very low (<30%), low (30-40%), medium (40-56%), high (>56%)
1. OECD statistics 2021 Municipal Waste Generation and Treatment and Eurostat, Circular Economy Overview 021 Waste Statistics
2. Based on assessment of interviewees

Figure 32. CE policies and practices in 2020-2021 for several selected countries and regions
Source: Cramer (2022)
CC BY 4.0

In Australia, changes towards the CE are driven by evolving standards and initiatives such as the **Interim Report by the Circular Economy Advisory Group**, the **Environmentally Sustainable Procurement Policy (ESP Policy)**, the **13 Circular Design Strategies by the NSW Government**, the **International Sustainability Standards Board (ISSB)** reporting frameworks and most recently, climate-related financial reporting legislation **(NGER Act)**, among others. Consequently, there is increasing pressure on major corporations to report on climate risk and sustainability outcomes, which would impact their suppliers. The expectation is that large organisations, especially tier-one companies, will increasingly demand sustainability assurances from their suppliers to align with investor expectations and ensure climate resilience. The growing emphasis on circularity means that embedding CE principles is now becoming a top priority in the industry, as evidenced by companies' internal efforts. Initiatives span various project phases, from engineering to procurement and contracting, thus requiring an integrated effort. As workshop participants commented:

> *'The new **ISSB (International Sustainability Standards Board) reporting frameworks** coming out mean major corporations are going to start having to ask these questions and start reporting on climate risk and reporting on sustainability outcomes.' (Adelaide workshop)*

> *'It really is **top of mind now**. Internally, we're doing a lot of things to make sure these principles and considerations are **embedded alongside**.' (Brisbane workshop)*

While there is enthusiasm for circularity, it is acknowledged that in the Australian context, the industry is still in the early stages of CE adoption and at the beginning of the learning curve, which is characterised by the experimentation and piloting phases. Participants recognised the need for diverse pathways to achieve circularity goals and acknowledged that companies' approaches to circularity will vary, often depending on specific departments, contexts, geographical locations and available resources. This is why piloting and experimentation are prevalent and it is critical to focus on assessing return on investment and implementing circularity scoring mechanisms such as the ***National Australian Built Environment Rating System (NABERS)***.

One participant commented on the learning experience and the need to receive more feedback on the outcomes of the CE:

> *'These new products that come on the line, they just in the **infancy** too. Sometimes you just need to **learn from experience**, and I think they will be more prevalent the more people use them and the more feedback that's out there.' (Hobart workshop)*

A key challenge is that the CE discussion is primarily linked to waste management and recycling rather than to a holistic approach encompassing all product life cycle stages as well as designing-out overconsumption. This narrowed focus limits the potential of the CE and disregards other potential and higher-level CE strategies, as explained by one of the researchers and experts in the field.

However, there is a growing momentum and Australian Government strategies are being developed to support circular initiatives, signalling a shift towards next-generation practices. The federal government unveiled an ESP Policy framework to use its purchasing power to support cleaner, smarter and more sustainable outcomes. It will contribute to extended life cycles of materials through a ReMade program to complement the Modern Manufacturing Initiative to improve supply chains. State and industry leaders are simultaneously taking steps to use their power and influence to support jobs and invest in sustainability.

> *'**Circularity is next generation**; I think Australia's really leader among probably a small group in that respect. That's why **I'm here to learn** as much as anything.' (Sydney workshop)*

> *'We've **just really started** to look at this quite seriously.' (Hobart workshop)*

The slow take-off of the CE is also a sign of complexity, lack of understanding, lack of CE measures and need for guidance.

Participants emphasised the need for guidance on achieving CE objectives and navigating the decarbonisation journey and net zero goals. This requires preparing the industry now and taking a holistic approach by targeting more than current waste management and recycling activities. Government and peak industry bodies play a key role in preparing and guiding the industry on this journey. As the participants explained:

> *'I feel that everyone is kind of not procrastinating really, but really a **bit careful with because of it's harder to measure**.' (Perth workshop)*

> *'Also, it's affected by our net zero ambitions so we have to be **preparing industry for it in detail**, not just for we can deal with that in 2030 or 2050. It needs to be happening now.' (Peak body representative)*

Circular economy in the construction life cycle

Design is the initial phase of construction (or pre-construction, beginning of product and material life), where circular design principles and strategies establish the foundation to minimise environmental impact and improve overall project sustainability.

Design plays a critical role in the CE and it is important to integrate new CE-driven principles and strategies by multilateral parties early in the design and planning phase. This will have a substantial impact on the construction process, the life cycle of products and materials in the supply chain and their end-of-life—it is claimed that 80% of the impact is locked in at the design stage (Ellen MacArthur Foundation, 2013). Therefore, architects and engineers have the responsibility to create and apply eco-friendly structures and principles when planning residential buildings, neighbourhoods and commercial and industrial parks to enhance quality and save costs while minimising environmental impacts. Assembling all the actors in the construction process and fostering collaboration was repeatedly raised as being key to facilitation.

Beginning of life – how to design?

Participants in workshops and interviews explained that their current design initiatives primarily focus on **energy and resource efficiency, net zero and decarbonisation**, the CE of **extended product life cycles** and **regenerating nature**. The discussions also referenced existing enablers and barriers for CE in design through policy and legislation (Figure 33).

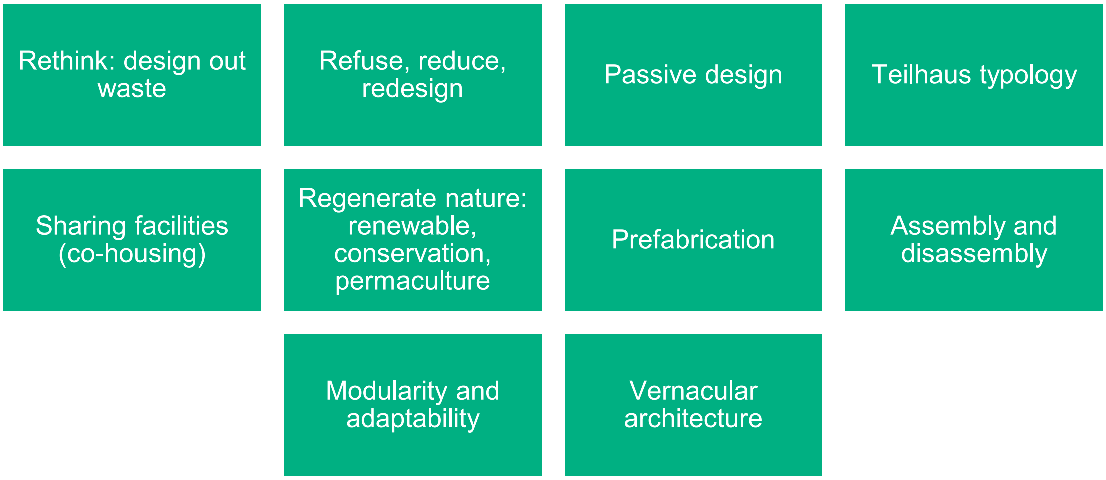


Figure 33. Circular design strategies in the built environment
Source: Own elaboration

The participants underlined the importance of **rethinking** design first, signalling the required mindset change to support the CE transition. For example**, designing-out waste** and problems from the supply chain was identified as a critical first step. It warrants asking whether a building needs to be built in the first place. Reference was made to European initiatives, such as the pre-construction carbon budgets in the UK, which raise questions about a project's necessity even at the pre-design stage (Environmental Audit Committee, 2022). Accordingly, central London regulations require proof that a building cannot be reused before demolition, thereby encouraging developers to preserve existing structures, as required with heritage sites—see an example of a heritage site in Australia in Figure 34. Participants explained the following:

> *'All the things that go into* ***asking the right questions. And even at the beginning****. I know the UK is starting to do this pre-construction with a carbon budget or circularity budget.* ***Does this project need to be built in the first place?****' (Sydney workshop)*

> *'I know central London has now put in some regulations where if you're going to knock down a building,* ***you have to prove that there is no way of reusing it.*** *And then you will have to choose to take six to 12 months of time if you want to go through that process of trying to prove that you can't use it. That creates a financial imperative on the developer, and a financial disincentive because you're losing time and you're losing fees to try and prove that it has to be knocked over, then it becomes easier to just keep the existing building and show that, we can put more weight on it.' (Architect interview)*

Participants referred to the hierarchy of CE solutions and 10R strategies (as presented earlier in Figure 9) and one participant specifically underlined the important role of higher-level CE strategies like **refuse, reduce, rethink and redesign**. As it was explained:

Figure 34. Harris Terrace, Brisbane, QLD
Source: Judith Herbst (2024)

> *'We really want to start off with refuse, reduce, rethink, redesign... till we go down to recycle and, you know, waste your energy.' (Researcher and external expert interview)*

Some companies have already started planning to reduce the amount of materials and waste in new construction projects, thus aiming to optimise resource use and minimise environmental impacts throughout the life cycle, such as water consumption and demand. In addition to **resource efficiencies**, these strategies are viewed as cost-effective and avoid risks such as supply shortfalls.

For example, references were made to the **supply chain complexities**. Since the COVID-19 pandemic, companies have been aiming to avoid supply shortfalls and reduce the risks. According to an architecture and interior design firm, planning for reuse can reduce the extra time of ordering and receiving the materials, as well as transportation. In addition, a government representative claimed that reusing spaces through adaptive reuse rather than designing new spaces should be considered to retain them at their highest value. Therefore, it shows the importance of identifying and minimising unnecessary waste.

> *'We're looking at the **whole life cycle from the planning and the design to downstream** what we do with the waste in the end, but the focus is more and more looking at **what do we do to prevent it, to design it out**—to get to that…but then going to reuse and how can we reuse spaces through adaptive reuse rather than even going down to building something new and how, if something new is being built, what's the potential for materials to be reused at its highest value before you downgrade heavy materials or introduce products with recycled content.' (Peak body representative)*

> *'It's important to **understand your waste and what doesn't need to be wasted**. Industry is quite conservative in the way it operates still on many levels, and that, you know, we need to change those things.' (Peak body representative)*

Passive design principles were identified as providing opportunities both in the design of new buildings and also in **renovating and retrofitting** projects (i.e., in the maintenance and life cycle extension of existing buildings). Passive design principles include changing the orientation of the houses and incorporating insulation upgrades and window replacements. These strategies can reduce energy consumption and maintain better temperature control. Accordingly, passive design has a focus on energy efficiency. Solar passive design strategies, which are slightly different, (i.e., solar passive houses) not only enable smaller footprints but contribute to extending the lifespan of buildings and result in a cost-effective, healthier and comfortable way of living **(Light House Architecture & Science)**. Participants commented on the passive design benefits as follows:

> *'We **design solar, passive, small footprint houses** that are incredibly energy efficient. In the Canberra climate, it really drives down the energy bills and keeps our clients cool in summer and warm in winter… We don't do passive house, we do solar passive design, it's a bit different.' (Canberra workshop)*

> *'You start with the environmental conditions. it covers the garden, then the building and then neighbourliness. First, you locate your garden on site because your garden unlocks solar access. Environmentally designed buildings are about getting the fundamentals right. They're not about the bells and whistles you place on them afterwards. If you've got a north facing window with a good room, you can cross ventilate it for Western Australian conditions. That's almost 80% of the battle because then all the building codes and **the green stuff will take care of the rest**.' (Architect interview)*

Light House Architecture & Science follows an agenda that is science-centric, to create *'light-filled, light-footed, all-electric, low-carbon homes and we aim to be a beacon for change in the Australian housing industry…it seems obvious that sustainability; protecting our environment; and designing for comfort, health and resilience in a rapidly changing climate should be integral to every business. Since 2011 we have been talking (very publicly) about how "smaller is smarter" and "bigger is not better." We have also been theoretically and physically testing houses since 2008.'* (Light House Architecture and Science, n.d.).

Solutions are also found in **co-housing**, where rezoning permits multi-uses. One example of innovative and communal development in the inner-city of Melbourne sheds light on a new model that created **shared facilities**, raising a sense of community and lowering occupier costs in a small footprint, passive-built environment (Kolovos, 2024).

In addition, new models have been designed for micro-housing units where facilities accommodate more people in smaller structures with communal areas. They raise a sense of community and security by lowering occupier costs in the smaller structures.

Evidence from the workshops pointed to the developers of the Nightingale Skye House commissioned by **Nightingale Housing** to Breathe Architecture. The non-for-profit organisation Nightingale Housing builds houses with apartments and shared facilities that are socially, financially and environmentally sustainable, following the build-to-rent unit design that helps society face the dual challenges of climate and housing crisis.

Nightingale Housing's design strategy also includes the **Teilhaus** concept, the German word meaning 'part of a house'. Teilhaus apartments are designed to be space-efficient, small-footprint homes that maintain their functionality by use of joinery and flexible spaces. Teilhaus apartments were incorporated into the Nightingale Sky House in Brunswick (Figure 35) and have since been integrated into other Nightingale Housing projects.

Figure 35. Nightingale Skye House is the first building in the Nightingale Housing project with a Teilhaus typology
Source: Breathe Architecture (n.d.)

Further, participants discussed the role of **renewable energy, water conservation, permaculture principles** and biodiverse landscaping as avenues for reducing environmental impact and enhancing circular economy in the built environment to enhance biodiversity and food production. However, this is an existing gap and despite its relevance and importance, there is a lack of applied examples of incorporating permaculture into the designs of buildings.

> *'I think the only thing that we potentially missed was something that we will be doing in the future, which is **incorporating permaculture into the designs of the blocks**. We're always thinking about the connection to the garden and with permaculture we're thinking about the productivity of the garden and how that can work to create an ecosystem in itself that provides food and uses the waste from the household to feed that as well.' (Canberra workshop)*

Figure 36. Heritage Lanes, Brisbane, QLD
Source: Judith Herbst (2024)

Participants also discussed the role of incorporating **biophilic aspects** into designs, with landscaping that promotes biodiversity in line with EMF CE's third principle to regenerate nature. Multiple tier-one projects embrace greenscapes. For example, Heritage Lanes in Brisbane (Figure 36) underwent a subtropical design to install ground floor landscaping, complete with a courtyard and a rooftop terrace of approximately 30,000 plants indigenous to the Queensland environment. They also set up a colony of 10,000 native bees.

In addition to energy efficiency, many eco-design strategies were addressed in the workshops and interviews and these were often associated with decarbonisation, material efficiency and material substitution, aiming to reduce environmental impact. For example, participants discussed designs for modularity that enable parts to be serviced, upgraded or replaced with **prefabrication techniques**. This technique incorporates prefabricated recycled materials and minimises disruption to residents during construction.

Moreover, lean manufacturing techniques and **design for assembly and disassembly** (see the ***Coreo and Built Design for Disassembly guide****), emphasising modularity, flexibility and simplicity, were highlighted as essential strategies and principles for creating adaptable and sustainable structures.

Coreo and Built – Design for Disassembly

At Green Building Day 2024, Coreo and Built announced the release of 'How to write a Building Disassembly Plan' guide. They provide practical guidance for creating a more sustainable, resource-efficient future for the built environment. They provide a questionnaire and a template to facilitate Design for Disassembly.

During the workshops, it was pointed out that the **Northern Territory military** has a history of designing facilities for efficient assembly and disassembly. Unlike most civilian projects, the Australian Defence Force applies a flexible, scalable construction design process, so buildings will be set up using design-for-disassembly techniques, for example, in remote communities. A peak body representative emphasised the need to develop skills within the industry to design for disassembly and pointed to the importance of embedding these skills in education and training skilled trades to provide this service, highlighting that Europe is more advanced in this area.

> *'We have to be building that capacity in industry here because of that need, which Europe is farther ahead. To be able to do **designing for disassembly, you need to have the skills to do that**, and then that needs to be **embedded in education**, having skilled trades that can provide that service.' (Peak body representative)*

In another case, an **XFrame** representative discussed their offering of demountable and modular wall-framing solutions and construction technology to reduce waste and promote reusability. Using automation and software solutions (such as Rhino modelling), every component aspect is calculated and the frame design is standardised to achieve a CE and minimise waste. Ultimately, they produce documentation, including assembly instructions, Q&A information, pack lists and everything their client needs to produce the product locally. As the representative explained, they work hand-in-hand with their clients to ensure the resulting projects meet the client needs and are also circular.

> *'We convert it into each frame and then we work with the architect through a negotiation to say does this meet your design requirements? How can we modify this to be more circular, more sustainable, more demountable?' (XFrame interview)*

Similarly, **vernacular architecture** entails designing structures and contracting the job, including material sourcing, which can happen in local areas so the project can be built in one place. This type of architecture is responsive to its environment and climate and builds on local materials. **Five Mile Radius** was mentioned for its ingenious conversion of materials into furniture from construction waste. They value the architecture of a specific place, landscape and people.

Furthermore, to foster local, evidence-based solutions, **CSIRO** has partnered with state and local government to set up Urban Living Labs, such as the **Darwin Living Lab** and **Western Sydney Living Lab**. This initiative aims to institute resilient urban development through co-innovation among industry, research and government and test various design strategies in their context to make the city more liveable, sustainable and resilient. The Darwin Living Lab is a 10-year initiative that serves as a testbed for tropical urban design to assess the effectiveness of heat migration measures. Therefore, these examples provide an R&D-driven approach to enable the incorporation of holistic and place-based solutions and provide the testing periods to create economies of scale for sustainability and liveability. CSIRO uses analytical tools to measure and monitor the performance of the results and make necessary changes.

The government also plays a key role in guiding CE design principles. For example, in a proactive manner, the **NSW Government Office of Energy and Climate Change** has launched its Circular Design Guidelines for the Built Environment. These design guidelines provide a great overview and practical applications of various design strategies. They aim to provide a whole-of-system approach to implementing CE principles and encourage all professionals and stakeholders to follow their 13 design guidelines, which can be tailored to the characteristics of each project. Their guideline provides a simple planning template focusing on each design strategy and specifying the project phase, aims and actions. This template encourages stakeholders to enrich their CE strategies. In addition, each design guideline is accompanied by a best practice example, both Australian and global. These are summarised in Table 11 below.

Table 11. Summary of NSW Government circular design guidelines and examples
Source: Office of Energy and Climate Change, NSW Treasury (2023)

#	Circular design strategy	Best practice example
1	Design for longevity	Leppington and Edmondson commuter car parks, Australia
2	Design for flexibility and adaptability	Circl Pavilion, The Netherlands
3	Design to maximise materials circularity and enable disassembly	Bradfield 'first building', Australia
4	Design for materials efficiency	Modern methods of construction in schools, Australia
5	Design for best practice operational waste management	Green commercial leases at Barangaroo South, Australia
6	Re-use existing assets or materials	Quay Quarter Tower, Australia
7	Select products with recycled content	M1 Pacific Motorway Tuggerah to Doyalson, Australia
8	Select products that are designed for disassembly	Het Diekmann Vocational School, The Netherlands
9	Select products and materials that have an identified recovery pathway	One Market Plaza, United States of America
10	Select low-impact materials	The Biological House, Denmark
11	Incorporate green infrastructure	Blacktown Showground water-sensitive urban design redevelopment, Australia
12	Maintain a materials database	Venlo City Hall, The Netherlands
13	Procure products as a service	M-use® elevator, international

Life cycle extension and maintenance

‘Around 80% of buildings in cities today will exist in 2050—we must urgently rethink the buildings we already have.’ (Grainger, 2022)

Extension and maintenance are considered during a building’s life. These CE strategies focus on preserving structural integrity, enabling repairs and implementing upgrades to prolong usability and enhance the sustainability of existing buildings. This phase is interconnected with design and is highly impacted by it.

During the workshops, participants indicated that multiple methods are employed within the construction industry to extend the life cycles of products and services. Queensland electricity and energy provider **Stanwell Corporation** spoke about how public infrastructure companies are investigating ways to reduce peak resource demand by increasing the capacities of existing assets to 'sweat those assets'. An existing pipeline system, for example, can include the capacity that allows for greater storage to delay upgrading a dam or building a desalination plant when augmentation is called for.

> *'**Augmentation can come through retrofitting**, rather than upgrading the entire length of the pipe, you might include a capacity in the system by including a storage or something and continue to supply the needs of different solutions. But all basically along the lines that if you apply circularity in systems like long linear systems like water lines and pipelines and on, and you want to think about demand management as an important first step.' (Brisbane workshop)*

Renovation and retrofitting

Refurbishment

Adaptive reuse

Participants discussed the role of **renovating and retrofitting**, which are crucial strategies that impact existing houses and structures. Reference was made to Your Home, Australia's guide to environmentally sustainable homes (yourhome.gov.au), which is viewed as a valuable resource for improving energy efficiency and reducing resource consumption in existing houses. These strategies encourage companies to constantly rethink how to make their buildings more energy-efficient and adaptable to the ever-changing climate circumstances. The focus should be on innovative strategies for repurposing existing structures to meet future demands sustainably. As participants claimed:

> *'The energy consumption is much lower post **retrofit**. It's a really good and **cost-effective option** for a lot of people in Canberra who want to keep their houses, but just need it to be more healthy and to function better for them. it's about putting in insulation in gaps, ceiling, replacing the windows and just overall that makes a huge difference.' (Canberra workshop)*

Engineering firm **Aurecon** agreed that retrofitting should be encouraged to transform existing assets rather than building new structures. However, to accomplish retrofitting, it is important to track the materials installed over time, such as steel and concrete in buildings, to understand how they can be maintained, repaired, or disassembled for repurposing. Participants discussed the potential of QR codes (further discussed in the *Technology* section) attached to specific materials, which are useful for monitoring usage and any changes to materials.

An architectural and design firm member also addressed how design can extend the longevity of buildings through **refurbishment or adaptive reuse**. These strategies highlight the need to consider existing buildings and structures and find a way to reuse these existing materials to optimise the operational and commercial performance of built assets. Therefore, the aim is that instead of tearing down the buildings, alternative strategies allow for repurposing them. This approach is exemplified in the ***case study of adaptive reuse: 47 Easey Street Collingwood*** below. Participants reflected on the role of existing buildings as follows:

> *'We've been using examples from all through **Europe** that you may be aware of, the kind of projects where **adaptive reuse of existing structures is totally the norm**, totally fine. It creates great housing, great adaptability, and has all the environmental, economic, and social benefits.' (Architect interview)*

> *'**A carer of buildings** is the same as a carer of humans, right? If one of your relatives has cancer, you don't put a bullet in their head. You don't go, that's it. You try and put them into a care program. It's the same thing with these buildings.' (Architect interview)*

Moreover, refurbishment, adaptive reuse, retrofitting and renovation could also play a crucial role in preserving **heritage buildings** by extending their lifespan and reducing waste, thereby maintaining their cultural significance while aligning with sustainable practices. For instance, Australia already has codes in place, the Burra Charter, to preserve heritage-listed buildings (Australia State of the Environment, 2021). Designers who create developments in highly congested urban areas have restored some outstanding landmarks, frequently by including social and biodiversity features. Under those conditions, buildings are repurposed for social, economic and environmental value.

Despite the benefits of adaptive reuse, it has not yet become best practice. For example, an architect explained that during a proposal process for a 14-story social housing tower from the 1960s *'not one of those proposals nor anything in the process ever mentioned an option of retaining the tower or adapting and reusing it..'* This oversight reflects a conventional mindset that prefers starting with a blank site rather than considering the potential of existing structural, environmental, or cultural conditions. Their environmental consultancy demonstrated that retaining and retrofitting the tower could save a year and a half in construction time and $13 million in costs while preserving embedded carbon. However, these advantages were not considered in the decision-making process.

Case study of adaptive reuse: 47 Easey Street Collingwood

BAR Studio, a Melbourne-grown international hospitality design firm, has restored the historic warehouse at 47 Easey Street, Collingwood, as its new studio and provides space to five tenants. BAR Studio is committed to sustainable practices in the development and operation of their studio. They engaged **REVIVAL** as the principal contractor, existing materials consultant and furniture maker. REVIVAL is a multidisciplinary practice holding B Corp accreditation, focusing on sustainable building design and practice. **HIP V. HYPE** was engaged as a group of sustainability consultants. HIP V. HYPE is an ethical, socially conscious and environmentally focused property developer, sustainability consulting practice and work share provider. BAR Studio is committed to fostering a culture of creativity, collaboration and exchange.

47 Easey Street is a two-story building mainly built from brick, wood and corrugated roof sheeting. The building has 1000 sqm floor space on the ground floor and another 1000 sqm on the first floor and is occupied by up to 80 employees. The design brief for 47 Easey Street was to transform the existing 100-year-old building into a fully compliant and efficient building and develop a new headquarters for BAR Studio's Melbourne team in a creative building community within a creative and socially progressive neighbourhood (Table 12).

During the *design and construction phase*, elements such as energy efficiency, water savings, better insulation of walls and windows, resilience to earthquakes, workforce wellness, end-of-trip facilities and reuse of materials had to be considered. The key pillars of adaptive reuse are reusing what you have, making the building structurally sound, fully insulating the building envelope and installing new, sustainable systems.

All exterior walls were internally insulated to fully insulate the building envelope and they received new linings. However, the original Baltic pine ceilings and timber floorboards are still visible. Support for solar panels (66kW) on the roof required a new structure, which opened the opportunity to insulate from above and retain the Baltic pine ceiling.

Parts of the structural construction of the 47 Easy Street building had to be exchanged or reinforced to make the building structurally sound. For example, 25 ground-floor structural jarrah columns had to be condemned as they were rotten in the zone between the concrete floor and the foundation. Therefore, all jarrah columns were replaced with steel columns. Changes to the NCC include seismic building bracing. The new steel columns were connected to bracing, which tied back into a steel band that circled the perimeter of the brickworks to improve earthquake resistance.

Table 12. BAR Studio case study of adaptive reuse photos
Source: Leonie Barner (2024)

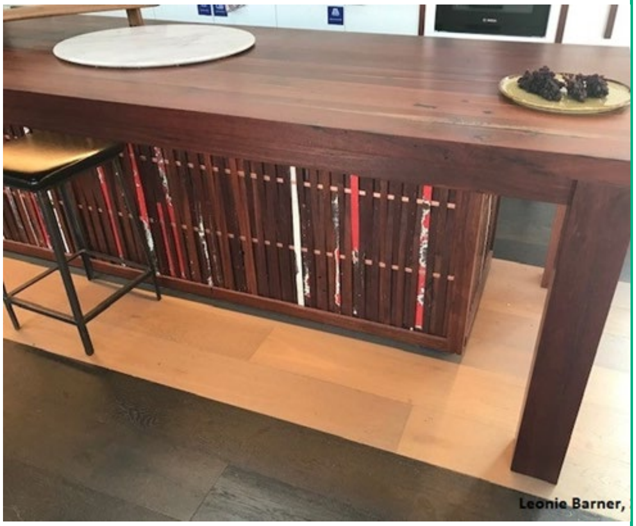
	
Original load-bearing wooden columns were replaced by steel columns. Steel crossbeams and bracings were implemented for earthquake resistance.	New steel load-baring column in foundation.
	
Water tanks to harvest rainwater for gardens and toilets.	Bike racks as part of the end-of-trip facilities. The first words of Revivals manifesto 'Frist Do No Harm' are visible as well.

Examples of reuse: Bricks that had to be removed during the renovation were given a new life as pavement bricks for the courtyard.

Examples of reuse: Pile of bricks waiting to be reused. Examples of bricks recovered from the building during the restoration. The brick in the upper left corner has been cut in half to be used as a pavement brick. Bricks are locally made.

Courtyard pavement made from salvaged bricks.

Example of partly rotten wooden load-bearing column. Left: Intact wood samples that were extracted from the load-bearing columns.*



Kitchen island made from on-site salvaged hardwood.

Vanities made from on-site salvaged hardwood.

*In addition, hardwood from the 25 load-bearing columns that had to be condemned was salvaged. Twenty-three of the 25 columns have already been repurposed back into the building. Five were used in the kitchen island, 1.5 for a DJ booth, 3 for a reception desk and others for joinery throughout the building, e.g., bathroom vanities and toilet stalls.

Doors of toilet stalls made from on-site salvaged hardwood and construction hoarding.

Old security grill put to new use in the courtyard. Security grills from the original windows are now used as a trellis for passionfruit in the courtyard.

The energy efficiency and thermal performance of the building were improved by replacing the old windows with new high-performance windows, which were locally made from Victorian Ash and solar ban 60 glass. Solar panels were installed on the roof and in-house battery storage was installed (100kW/250kW). Further, rainwater is captured and stored in tanks (30,000 L capacity) for use in the garden and toilets. 47 Easey Street has 18 bike parks with end-of-trip facilities and two electric car charging stations. The building also has a solar-powered Tesla lift.

End of life – new beginnings?

Resource recovery and waste management are the end phases of the construction process and product and material life. The focus is on responsible disposal, recycling and repurposing of products and materials. Although waste management signifies an endpoint, it is interconnected with design and, thus, the *beginning* of the process.

Recovery, reuse and recycling of C&D waste are important aspects of the CE in the building and construction industry. C&D waste is reported in the biannual National Waste Reports and covered by the Australian Standard for Waste and Resource Recovery Data and Reporting ('The Australian Standard'). The C&D waste stream is defined *as 'waste produced by demolition and building activities, including road and rail construction and maintenance and excavation of land associated with construction activities.'* (Pickin, 2024, p.4). The Australian Standard for waste and resource recovery data and reporting (Pickin, 2024) defines building and demolition materials as asphalt, bricks, concrete and pavers, ceramics, tiles and pottery, plasterboard and cement sheeting, soil, sand and rock. C&D activities produce other types of waste, such as metals, organics, paper and cardboard, plastics and glass.

In 2020-2021, C&D core waste generation was 25.17 Mt, with an additional 2.07 Mt from other waste sources, excluding ash. Core waste, i.e., materials from C&D, commercial and industrial and municipal solid waste, accounted for 63.8 Mt of waste. However, the overall waste generation, i.e., additional waste such as ash, organic primary production, organic processing, mining and mineral processing, resulted in 757.7 Mt of waste in 2020-2021 (Pickin et al., 2022). Fortunately, the C&D material recycling and reuse rate is high at 80%. Therefore, C&D waste has already reached the National Waste Policy Target 3, i.e., 80% average resource recovery rate from all waste streams by 2030 (Australian Government, 2019). Nonetheless, there is room for improvement and some waste and recycling companies report an average resource recovery rate of over 90% (Department of Environment and Science, 2019).

In addition, many waste management companies are shifting to become waste management and recycling companies due to pressures from landfill levies, reduced availability of landfill sites and resource scarcity. Considerable efforts are made to recover as much material as possible to minimise the amount that is disposed of in landfills.

> *'Because the landfill levy was implemented here quite early, it has **contributed to the diversion of C&D**. That made a difference to where the state is today, which means that we can now focus on another side of work. We want materials reused in the first place, and then you can look at the next best thing.' (Peak body representative)*

In addition to recovering, reusing and recycling materials, another key focus is the **decarbonisation of vehicle fleets** (see more in the ***Future Fuels CRC****). This impacts the embodied energy of building components by reducing the impact of transportation GHGs. For example, hydrogen is considered a promising option for heavy vehicles. Waste companies could produce hydrogen by collecting water from vehicles and using electrolysis, as well as from landfill gas, organic waste, or plastics, and this way contribute to the CE.

***Future Fuels CRC** – Decarbonisation of Australia's energy networks*

Through collaboration and outcome focused research, the Future Fuels CRC will enable Australia's energy sector to adapt its infrastructure to net zero emissions fuels by providing knowledge and facilitating its use by industry. The Future Fuel CRC will transition energy infrastructure to a low-carbon economy using fuels such as hydrogen and biogas.

Future Fuels CRC research programs encompass: Future Fuel Technologies, Systems and Markets; Social Acceptance, Public Safety and Security of Supply; as well as Network Life Cycle Management.

Representatives of two Waste Management and Recycling companies were interviewed: **Wanless** and **Waste Management Company II** (who opted not to be named in this report). In addition, a site visit to the Wanless Recycling Centre in Western Sydney was undertaken.

Both companies are vertically integrated in the waste management and recovery/recycling sector, from the collection of waste and transfer stations to processing recovered materials and landfilling any material they cannot recycle. There is a growing trend that customers ask for better recovery rates and better circularity outcomes, i.e., as high as possible. C&D waste from construction sites is collected in skip bins. Some builders start to source-separate at the site and will separate metals, masonry materials and soil. This results in a lighter mixed waste stream with plastics, timber, cardboard and concrete. Better waste separation at the building and demolition site would be desirable, but space for additional skip bins is an issue. Reference was made to **Precycle** in South Australia, which specialises in on-site waste separation, concentrating on removing and recycling discarded building materials from residential construction sites.

Figure 37. Metal separation at Wanless facility
Source: Leonie Barner (2024)

As the waste management company representatives explained, when C&D waste is delivered to the recycling facility, it is first checked for **contamination**, such as food waste, batteries, asbestos, chemical drums and vapes, which often need to be removed manually. Subsequently, the C&D waste is separated by material type using screens, magnets and methods based on density and weight (Figure 37). Over the past five years, the demand for recycled materials from manufacturers has increased. Consequently, a variety of products containing recycled materials, such as concrete, particle board and carpets, are now available for purchase.

Nonetheless, as highlighted by a peak body representative, one challenge of creating infrastructure for waste separation is compounded by the **lack of adequate storage solutions**. The representative also referred to a study at Knox Industries, which seeks to assess what is going into the waste, what waste can be separated and the existing takeback schemes. The CE and market development in the built environment currently focus on on-site waste separation. However, there is a notable gap in the market when it comes to waste separation for residential builds. Efforts are made to integrate further circular options and enable circular systems, where there are opportunities for repair too.

> *'Our customers have told us over and over again that **they don't have space**.' (Waste management company II)*

> *'The agency is responsible for the state waste strategy. A lot of what our agency **focuses on is materials and resource recovery**, but a lot of the regulations sit with planning. And we're looking at more circular systems in larger developments and precincts where there are opportunities to build in repair services.' (Peak body representative)*

Another challenge in implementing efficient waste separation mechanisms is the **transient workforce on building sites**, resulting in difficulties in educating workers regarding waste separation. Challenges were generally identified as space and behavioural issues with separating waste on-site followed by costs. Specifically, as an initial step, it would be desirable to train the workforce in separating PVC from other plastics (see ***Construction Plastics Recycling Scheme****) (see Figure 38), to collect cardboard separately, as well as batteries and single-use vapes.

Vapes (part of the construction workforce has switched from cigarettes to vapes) and batteries (e.g., from power drills) are especially problematic if mixed with other waste as they are a fire hazard. As soon as they get crushed by compacting the waste (which is a normal process for waste management), the lithium batteries will combust in an explosive manner. Both waste management companies reported fires in waste trucks caused by lithium batteries, which resulted in the ejection of the truckload onto the street to extinguish the fire. Lithium batteries have also caused fires in recycling facilities. This not only reduces the circularity of materials but also poses significant social and safety hazards.

****Construction Plastics Recycling Scheme***

In November 2021, Master Plumbers' Association Queensland (MPAQ) and Plastics Industry Pipe Association of Australia (PIPA), in conjunction with Vinidex, Iplex, Tradelink, and Reece, launched the Construction Plastics Recycling Scheme.

Funding is provided by the Queensland Government's Recycling and Jobs Fund. There are 14 PVC drop-off points in Queensland and Phase 3 aims to expand to 40 bins. The scheme also runs educational programs via TAFE to inform plumbers what materials are acceptable and not acceptable in the collection bins to reduce contamination. To date, 2.1 tonnes of PVC piping has been collected, and 93% of it was recycled into new PVC pipes.

Figure 38. Bin from the Construction Plastics Recycling Scheme
Source: Leonie Barner (2024)

An additional problem is the **insufficient capacity** in Australia to recycle batteries. Currently, lithium-ion batteries need to be stockpiled because battery recycling facilities are at capacity.

> *'With a linear product or project, you have got a limit that you can hit in terms of circularity.' (Waste management company II)*

> *'Unless you genuinely think about how this will be deconstructed, you are kind of stuck.' (Waste management company II)*

From demolition to deconstruction

In traditional, business-as-usual practices, a building's end-of-life is marked with **demolition**. However, in a CE, there is a push towards **designing for deconstruction** rather than demolition. This is a key step in the CE journey of construction companies. It implies a mindset change and emphasises the value of materials and the potential second-life materials can get at their end-of-life and after their intended demolition. This includes various strategies, as summarised in Figure 39.

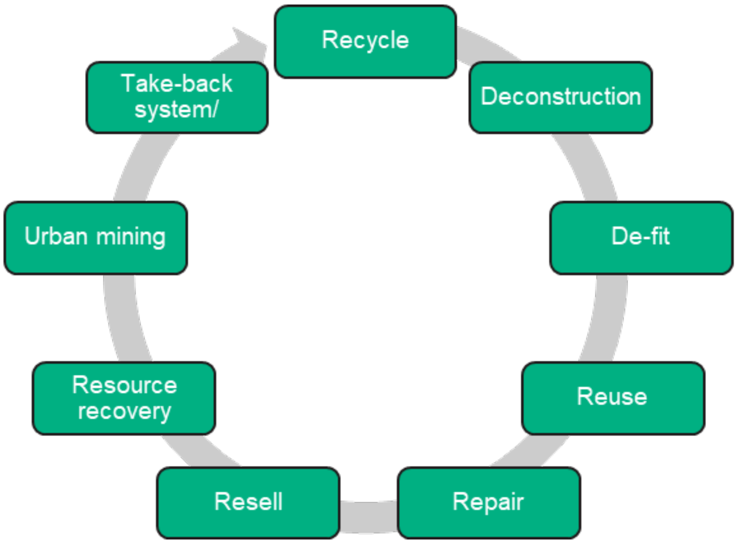


Figure 39. End of life and recirculation strategies
Source: Own elaboration

Design for deconstruction was piloted by an architecture and interior design firm. They started to audit the resource recovery potential from construction sites to value the items that are being removed. They demonstrated an opportunity to find new ways and purposes to reuse, repair and resell construction materials, thus reintegrating materials and products into the supply chain. These audits highlight opportunities for waste minimisation and underline the economic value inherent in materials removed from construction sites. Therefore, in a shift from demolition to deconstruction, the end of life of materials is considered at the beginning of the life cycle stage and the concept of deconstruction suggests that companies think in terms of second and third lives.

Another case in point is **NTEX**, a demolition and civil contractor operating in the defence and private industry in NT. Their services include recycling uncontaminated material, particularly concrete and asphalt and recovering solar systems and white goods to save them from landfills. Their machinery can extract metal rebar, plastics and other waste streams on site up to a 99% crushed and screened pure product (or whatever specification is desired) for reuse in roadbuilding, foundation, or drainage works. Thus, it does not require transport, which improves safety and saves extraction of finite resources and budget (considering that transport is mentioned as a large cost factor). The company also partners with metal recyclers. They have maintained records since 2020 using Excel spreadsheets to track the flow of waste, previously averaging a 93% recovery rate across all their demolition projects. This level has declined due to fewer recent opportunities for recycling in remote communities and disaster management work. In addition, testing for asbestos, Per- and Polyfluoroalkyl Substances (PFAS) and other toxic substances is critical to preventing harm to health and the environment.

Urban mining shows the untapped potential of materials existing within cities, advocating for a shift in perspective towards viewing waste as a valuable resource awaiting exploration and utilisation.

> *'We really haven't looked at **how do we change the way we look at waste and rather see that as a resource that's sitting in the cities**. We have aluminium, glass, and other materials all in the city, it's distributed and we really should be looking at exploration permits for companies to look at how do we get some of that material into circulation.' (Brisbane workshop)*

Nonetheless, a significant challenge in designing for deconstruction and incorporating the aforementioned CE strategies remains the *'material and information redirection gap'*. The key to transition is developing more cohesion and there is a need to establish market demand and a viable CE marketplace infrastructure, such as a takeback system or a reverse infrastructure, with sufficient understanding and information about the CE processes. While efforts are made to divert materials from landfills, ensuring sufficient demand for repurposed products remains critical to achieving a CE in the Australian construction sector.

As an example of **market demand**, reusing materials creates new value chains, such as initiatives to reuse phosphorus and biosolids from wastewater treatment plants. Then, the previously presented example of reselling or donating items such as white goods and solar systems to contribute to waste reduction and resource conservation is also reliant on understanding where these materials should go.

A Hobart workshop participant talked about an example of a reverse loop, with reference to carpet and lining producers, **Interface**. They are a global leader in modular flooring who implemented a takeback infrastructure to facilitate the reverse operations. They show proactive approaches to material stewardship by offering to reclaim products at the end of their life, such as used carpet tiles, which are redistributed through their partner network. By doing so, they contribute to closing the loop and minimising waste generation. At this point, materials like concrete and steel could be reintegrated into new construction projects, thus going from deconstruction to construction.

However, another issue is a **lack of regulatory requirements** for repurposing materials or waste and the focus remains on individual efforts to optimise resource utilisation. For example, many efforts to recycle materials are driven by partnerships with recyclers and a growing awareness of the CE's environmental benefits, including reduced truck miles, increased material reuse and improved tracking of resource recovery rates.

Case study of de-fit and upcycling: Stockland

Stockland participated in two circular projects at their multi-use, master-planned communities for social, economic and environmental value. First, they carried out a de-fit at a vacated commercial premises, a former Flight Centre at the Merrylands Shopping Centre and subsequently they set up a mobile food vending site and bakery at The Gables in New South Wales from inventory.

De-fit of a retail store

Early in 2023, **Stockland** commissioned **FTD Circular** to de-fit and divert 100% of the interior assets from a retail outlet. Multiple triple bottom-line impacts were actualised through this initiative. Construction materials and supplies were forwarded to build a new art space and resident library. In total, 100% of the assets (fit out fixtures, fittings, equipment and furniture) and 87% of inventory categories (materials by the sqm or linear m) were redirected. Many items were donated to Mission Australia, recycled by BM Recycling and sold via Facebook Marketplace. The following items were grouped and transported to BM Recycling (Table 13).

Table 13. Recycled construction supplies and materials in Stockland case study
Source: Stockland (2023)

Construction supplies/materials	Quantities
Light fittings, cable, power points	200 kg
Glass	720 kg
Concrete, tiles	640 kg
MDF, joinery board	360 kg
Metal – aluminium, steel	180 kg
Plasterboard	1.04 tonnes

Data were stored on an FTD Circular/Hardcat Lebosi digital asset management platform, and the estimated embodied carbon of the assets and inventory sold, donated, and reused (for all available information) was 1,775kg CO_2e. The library fixtures, fittings, and carpet as virgin are estimated at around AUD 40,000, thus showing savings for raw materials and manufacturing. Transport was covered by the contractor and recipients of the goods.

Although the de-fit had a quick one-week turnaround that limited repurposing options and incurred labour and logistical costs, Stockland reduced waste and fees associated with sending the materials and supplies to landfills. Further, they helped many people who received items during a cost-of-living crisis while fulfilling their social corporate responsibility.

FTD Circular suggested ways for Stockland to reach higher circular outcomes in the future by modifying its design and fit-out guidelines, as follows:

- Examine alternatives to industry-standard flexi ducting and support investigations of re-use and recycling initiatives for this problematic product.
- Support the use of split batten and other modular and mechanical mounting methods for wall fixtures, displays, panels and finishes. These methods are used extensively and safely in museum exhibition design and they greatly facilitate the easy upgrade of fit-outs and re-use/redeployment circularity.
- Maintain separate underlay and carpet tiles because the lack of gluing in this instance enabled better reuse without sacrificing performance.
- Reuse glass shopfronts and ingo ramps if they do not require replacement by the next tenant's shopfitter.
- Keep back-of-house finishes, fixtures, floorings or other second-hand resources that are in good condition and do not need to be rebranded by an incoming tenant.

Significantly, having sufficient time and a budget to manage these projects can bring more ambitious results. Building in timeframes for deconstruction is critical because dismantling a site and separating materials requires planning and space to conduct a de-fit in an efficient and safe manner. At a commercial facility, it would be ideal to have collection bins for segregating different waste streams destined for recycling transfer stations and single-stream waste recyclers.

Upcycling to assemble a mobile food vending site and bakehouse

Stockland heeded those recommendations later that year by upcycling construction materials to establish the indoor and outdoor areas of a bakery and mobile food vending site at The Gables master-planned community in Hills Shire, part of Sydney's ever-growing North West. Management engaged with community residents and organised barista and baking courses with the local Santa Sophia College for work experience opportunities.

The project was designed to maximise disassembly. It reflected creativity and demonstrated endless options for adaptive reuse. All elements were accounted for in a database to enable future repurposing.

End-of-life materials were collected from varied places—houses, farms and commercial establishments—that went to an inspection hold point and were reserved for all reclaimed materials. Salvaged bricks were applied to the paving and walls. A shearing shed was adapted to erect a glass house. A school bus was transformed into a food and beverage shop, corrugated roofing and trusses were converted into shade structures, mature trees were transplanted and irrigated with recycled water and shipping containers were refurbished to create a toilet block, storage and cool rooms (see Figure 40). Although this project required time, hiring consultants and contractors and construction cost of AUD 1.7 million for Stockland, management was committed to attaining circular outcomes.

Figure 40. Under construction—Bobby's Bakehouse and the pie bus, resurrected from an old school bus and other materials on site
Source: Stockland (2023)

Case study of deconstruction and collaboration: CommBank stadium

The CommBank Stadium in Parramatta is a 30,000-seat rectangular stadium with the steepest grandstands in Australia. It is used for sports (rugby and soccer) and entertainment, cultural, community and business events. The CommBank Stadium is situated next to Parramatta Parklands (listed on the UNESCO World Heritage Register) within the World Heritage buffer zone. It is now a very high-quality destination within a Parkland and heritage context. Its build was completed in April 2019. The CommBank Stadium is operated by Venues NSW. **Lendlease** was the developer of the CommBank Stadium and, early on, assembled a consortium spanning partners such as **Populous** (architectural design), **Aurecon** (engineering), and **BlueScope Steel** (steel manufacturer), among others.

The building brief for the new stadium was prepared by the NSW Government, and they identified an opportunity to develop a stadium as a catalyst for Paramatta's broader urban regeneration, driving progress in sports as well as bringing major economic benefits to Paramatta and benefits to the local community. The brief also included the provision of active and passive recreation elements that could be used by the local community all year round.

Lendlease's aim for the consortium was to deliver the project on time and within budget while addressing the building brief. Critically, concepts of CE, such as reusing material from the soon-to-be-demolished stadium, procuring off-the-shelf locally available materials, and designing for deconstruction, were central to achieving these targets. The cornerstone of the successful delivery of the CommBank Stadium was **collaboration by all parties** involved in this project and early engagement of all partners, enabling great understanding across all aspects of the project and identifying and subsequently addressing problems early on, therefore saving time and budget. The consortium ensured that representatives of the whole supply chain of building materials, such as BlueScope steel, were present during key design stages.

> *'This project would have not been successful if there wasn't the **collaboration between all parties**.' (CommBank interview)*

> *'**Contractor involvement in projects like this at an early stage** has become something which de-risks projects.' (CommBank interview)*

For Populous—which was responsible for the architectural design of the new stadium—it was important to showcase the raw industrial nature of the stadium in keeping with the character of Western Sydney and implement industrial aesthetics, reminiscent of the Sydney Harbour Bridge.

The stadium consisted of four main structures: the foundations, the superstructure, the bowl and the roof. The main materials used were concrete, steel and roof fabric. The 360-degree continuous seating bowl brings spectators as close as possible to the field of play while providing the best viewing quality. Concrete was used in the foundations and the seating bowl. Considerable amounts of concrete for the seating area in the south and north stands were precast, enabling speed of construction and standardisation of precast concrete elements. All seats and handrails are securely bolted to the concrete, with a section of convertible seating provided in the north stand. This allows for easy transformation to suit different event modes. The seating can be adjusted from traditional seated positions for rugby fans to safe standing positions for football fans, offering flexibility and safety for both types of events.

This adaptable design has been used for the first time in an Australian stadium.

The consortium decided early on to develop a design that was simple and as flexible to construct as possible, also enhancing the speed of construction and safety. The roof frame is a steel structure constructed from steel beams that are bolted together, not welded, enabling assembly of as much of the roof structure on the ground as possible, and then lifting it into place quickly and safely. This minimised manual labour, especially at heights or on sites with greater risk of injury. Bolting the steel beams instead of welding them also enabled the possibility of deconstructing/disassembling them and reusing them at other sites. The steel beams—designed in collaboration with Populous, BlueScope Steel, and Aurecon—were produced locally by BlueScope Steel and delivered by standard trucks to the construction site. Another design advantage was that the roof did not have to be constructed in sequence, i.e., the trusses from the northern side could have been installed at the southern side and vice versa, providing flexibility to the construction process. Delivering the project on time also meant de-risking supply chain delays by producing construction components locally, such as the steel beams at local BlueScope Steel production sites.

Another important design element was to use as little material as possible to reduce embodied carbon. For example, the northeast and south concourses do not have any cladding (therefore, no secondary steel and cladding materials are used), enabling natural ventilation. As a consequence, no mechanical ventilation system is needed, reducing both building and operation costs. Having no façade also enables natural lighting during the day (Figure 41).

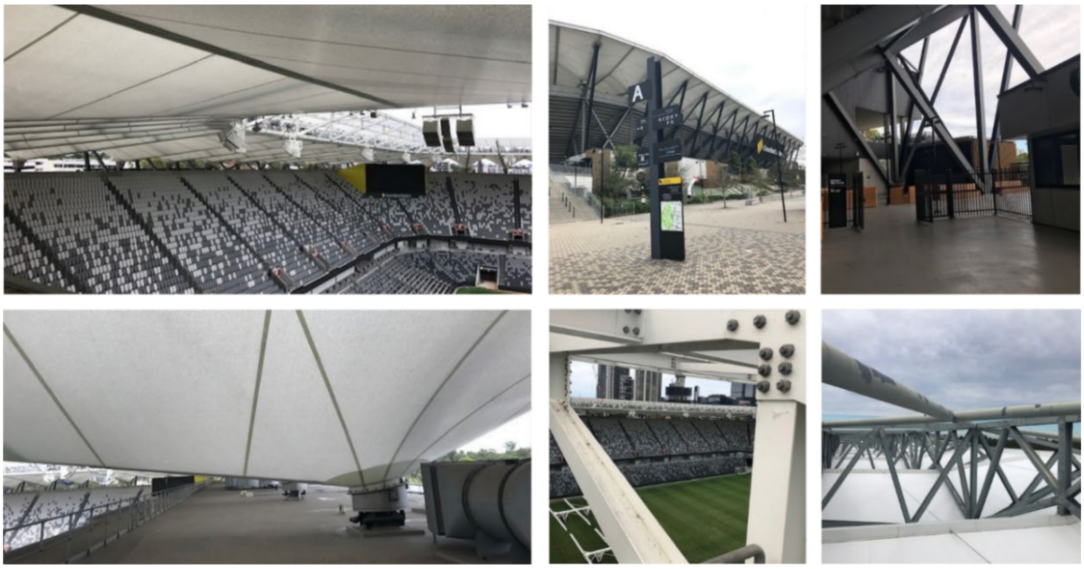


Figure 41. Circular design implemented at the CommBank Stadium
Source: Leonie Barner (2024)

The material consumption was also reduced by using a fabric for the roof instead of steel. Another advantage of fabric as a roof cover over steel was the speed at which fabric can be installed. The fabric was installed beneath the steel frame rather than on the outside, creating the illusion of an elegant, floating fabric roof soffit that hides all horizontal structural elements from view and enhances the intensity and atmosphere of the seating bowl, adding to the overall viewing experience. In addition, water is harvested from the roof fabric and is used for irrigation, saving on town water supplies.

Instead of using metal halide lights, LED lights were installed throughout the stadium, resulting in energy savings and achieving a LEED Gold certification (Figure 42). Photovoltaic (PV) cells are installed on top of the Western stand building roof, covering some of the stadium's electricity demands. Design for Maintenance was also considered by providing easy access to areas such as stadium spotlighting and PV panels.

During event days, no car parking is available for the public next to the stadium, encouraging the use of public transport, i.e., buses, heavy and light rail, ferries, as well as walking, connecting people to their city and the stadium.

Figure 42. LED lights at the CommBank Stadium
Source: Leonie Barner (2024)

Along O'Connell Street, just outside the stadium, there are dedicated play spaces with passive and active recreation elements such as seats and a tree canopy, half-court basketball courts and exercise equipment. The stadium also has a family seating zone, roughly twice the size of the previous family stand at the old oval, with direct connections to a Kids' Zone and nearby family activation areas.

The team from Venues NSW, which is managing the CommBank Stadium, is closely monitoring the consumption of electricity, gas and water and the amount of waste produced. They are continually updating the facilities to reduce the environmental impacts and extend the stadium's lifetime. They are also closely monitoring the stadium's environmental impact on the adjacent Parramatta Parklands (e.g., the flying fox colony).

Material selection

Architects, engineers, procurement professionals and environmental consultants are key in material selection. The type of material they choose has critical impacts on the remaining supply chain and the life cycle of the products, making them integral to the building industry's sustainability efforts.

In the materials production, procurement and selection domain, the findings highlighted several key considerations and strategies to promote sustainability and CE within the construction industry. Companies are also beginning to address decarbonisation initiatives in the production of materials.

Participants underlined the key role of **procurement practices** in the construction industry. It is important to understand the origins of products and evaluate materials for their environmental impact. The participants shared examples of conducting circular scans and environmental assessments to guide procurement decisions and develop sustainable procurement options. Eco-label certifications, such as those provided by **Good Environmental Choice Australia (GECA)**, were highlighted as valuable tools for identifying environmentally friendly materials and products. The **embodied carbon content** of building materials was a significant discussion point, with participants stressing the importance of selecting materials with low embodied energy.

> *'We are **developing circular scans, environmental assessment of materials, and road maps for specific industries throughout the different markets in interlocks of energy, water, precincts,** and built environment. It is a lot **on procurement processes as well**.' (Adelaide workshop)*

> *'In terms of looking to circularity in the way we design, it is a lot about selecting materials that have a **low-embodied energy**.' (Canberra workshop)*

This research identified several strategies that can significantly contribute to promoting sustainability and circularity in **material selection**, including material substitution (see, for example, the **HILT CRC and their suggested solutions for carbon-neutral materials***), the use of composite materials and durable materials that can extend product use and the facilitation of reuse, remanufacture and recycling to keep the materials in circulation and minimise waste. The aim is to use less material while maintaining their performance. The shift from demolition to deconstruction (as previously presented) allows companies to recover resources and disseminate knowledge about demolition companies that can extract, retrieve, test and even reuse materials on or offsite for civil construction. This is particularly crucial for health & safety and profit (partnerships may form).

*__*HILT CRC__ – De-risking decarbonisation for heavy industry*

*The HILT CRC develops and demonstrates the technologies needed to transform Australia's heavy industry to compete in the low-carbon global economy for **carbon-neutral materials** such as green iron, alumina, cement, and processed minerals.*

HILT CRC research programs encompass: Process Technologies including technologies and methods for production of low-carbon construction materials; Cross-Cutting Technologies; and Facilitating Transformation.

Traditional materials

The findings cover the traditional materials of **steel, concrete, timber, glass, plasterboard, clay or mudbrick, stone, polymers and aluminium.**

Steel is viewed as one of the most recyclable building materials available, which is underlined by the **Australian Steel Institute**. They promote an integrated effort towards enhancing the reuse and remanufacturing of steel, contributing to the industry's ongoing decarbonisation efforts. Interestingly, discussions revealed steel as a viable alternative to concrete, especially in remote settings where concrete accessibility and quality remain challenging. For example, recovered metals such as steel and aluminium are sold to metal recyclers. Moreover, steel's resilience against termite damage makes it a preferred option over timber in certain contexts. Notably, the life cycle of steel can be extended beyond initial use (thus keeping the product in circulation). Specifically, participants talked about steel finding new life in subsequent projects, particularly in structural and reinforcing steel

*__*SmartCrete CRC__ – Towards net zero concrete by 2050*

The SmartCrete CRC develops fully integrated product development and systems capability, from research proof-of-concept to commercial production stage, that is ready to roll-out and will lead to Australian competitiveness in Design Engineering and Advanced Manufacturing. The research streams cover sustainable concrete, engineered solutions, asset management, and industry challenges.

applications. Companies like **BlueScope Steel** are pioneers in this field, offering steel products catering to various construction and infrastructure needs, from roofing applications to framing and beyond.

Concrete was also discussed as part of construction processes for potential circularity. For example, participants discussed recycling bricks and concrete by crushing them down into aggregates and repurposing them as a subbase for new developments, such as bedding sand for construction projects, thereby reducing waste and environmental impact. However, despite its widespread use, concrete has no significant replacement due to its durability and structural properties (for more information on net zero initiatives in concrete, see **SmartCrete CRC***).

Timber also emerged in the findings concerning categorising timber buildings based on the type of treatment and the specific type of timber used. For example, recycled timber can be used in floorboards, benchtops, joinery and lightweight cladding for low-embodied energy **(Light House Architecture & Science)**. Further, recovered timber not treated with copper chrome arsenate (CCA) can be used for particle board manufacturing, although CCA-treated timber needs to be disposed of in a landfill. There is interest in tracking timber quantity and sourcing to ensure responsible practices. Nonetheless, issues related to the timber supply were raised, specifically the need for bushfire-compliant timber (particularly important in Australia).

Recovered **PVC** is sold to companies to produce PVC piping. **Plasterboard** can be sent to a third-party recycler (e.g., **REGYP**) that shreds and screens it, with gypsum going into agricultural markets as a soil additive and cardboard for further recycling (Figure 43).

Figure 43. Recovered gypsum at Wanless recycling facility
Source: Leonie Barner (2024)

REGYP provides plasterboard and gyprock waste disposal and recycling services via disposal points, skip bins, and truck pick-up services from building and construction sites. **REGYP** can also provide a full waste report required for **Green Star** certification (a GBCA rating tool).

New and alternative materials

The findings highlight the new and alternative materials of **hemp masonry, straw bale, rammed earth, algae concrete, green roofs and walls**. There is a potential for bio-based alternatives to mitigate environmental concerns associated with conventional building materials and there is a need to demonstrate healthier material options in practice. These innovative solutions, including natural building materials, are opportunities for alternative materials to replace traditional materials with newer and safer composites. The goal is to lower the extraction of resources and waste and companies are often driven by decarbonisation regulations to mitigate their impact.

Initiatives like capturing phosphorus and ammonia from wastewater were discussed as part of a broader approach to sustainability that considers planetary boundaries and resource management. Other examples referenced lightweight, low-embodied energy and water-based adhesives that do not require solvents, so they can break down again, and substitute petroleum-based adhesives in products **(Crafted Hardwoods)**. However, there are limitations in wet and high humidity environments and those where water leakage may be an issue.

Further, participants discussed innovative projects that are exploring bio-based alternatives, such as ***green concrete*** as a lower carbon and less harmful alternative or ***algae-based concrete*** for cement, which offers the potential to reduce carbon emissions associated with traditional cement-based geopolymer concrete (this project is currently underway, at the time of the writing) **(SOM)**. In addition, ***hempcrete*** has emerged as a potential alternative that is readily available in Tasmania **(Skookum Building & Design)**. These approaches reiterate the natural and regenerative focus of the CE.

Nonetheless, it is important to note that incorporating bio-based materials does not automatically reflect low-embodied emissions. Therefore, its adoption should be critically assessed as an alternative **(Light House Architecture & Science)**.

> *'I think that is why I gravitate much towards the alternative building materials that are natural materials because it takes away that need for adhesives, and it ensures **you are using something that can go back into the ground**.' (Canberra workshop)*

Moreover, combustible residuals that cannot be separated can be transformed into alternative fuels for the cement kiln industry and some power plants. Samples are analysed to prove they do not contain treated timber or PVC.

Case study of wood reuse: Sumitomo

Sumitomo Forestry is a Japan-based owner, manufacturer and distributor of wood products. Its global construction and real estate divisions are expanding in Asia and Australia, with several home-building subsidiaries constructing detached homes. **Henley Homes** is located along all eastern seaboard states and SA. **Wisdom Homes** is a project home builder concentrated in Sydney. **Scott Park Group** is a residential building and finance group that is dispersed across Perth and regional areas of the South and Midwest in Western Australia.

These building companies take innovative approaches towards sustainability. Henley Homes set a precedent as Australia's first major national builder to install solar panels as a standard inclusion in its homes, contributing to the Commonwealth Government's aim to reduce Scope 3 emissions. The parent company, Sumitomo, has already achieved a carbon-negative position under Scope 1 and 2 emissions through the absorption of CO_2 emissions by the forests that it globally owns and manages.

Figure 44. Responsible cleaning practices after on-site jobs
Source: Slurrytub (2024)

Henley Homes also engages a third-party waste collector to sort items for reuse. They joined **SLURRYTUB** to patent a cleaning solution that filters and drains wastewater cement slurry after bricklaying, tiling, rendering and plastering into a protected tub on site (Figure 44). The SLURRYTUB is a robust, recyclable plastic container equipped with a biodegradable paper filter. It allows visibly clear water to drain within designated washout areas or be recycled. Once the waste has dried sufficiently, the hardened material and the biodegradable filter can be disposed of in the work site skip or through another approved disposal method.

In Australia, Sumitomo is now partnering with global real estate investors such as Hines. They recently completed the development of Melbourne's tallest timber tower, a 15-floor office building in Collingwood, using Victorian oak responsibly sourced from Australian forests (Figure 45). The facility embodies a T3 branded strategy to advance *timber, transit and technology* that seamlessly integrates environmental and social sustainability with its proximity to public transport and amenities. In addition, its cross-laminated timber (CLT) structure makes the building lighter while reducing whole-of-life carbon emissions.

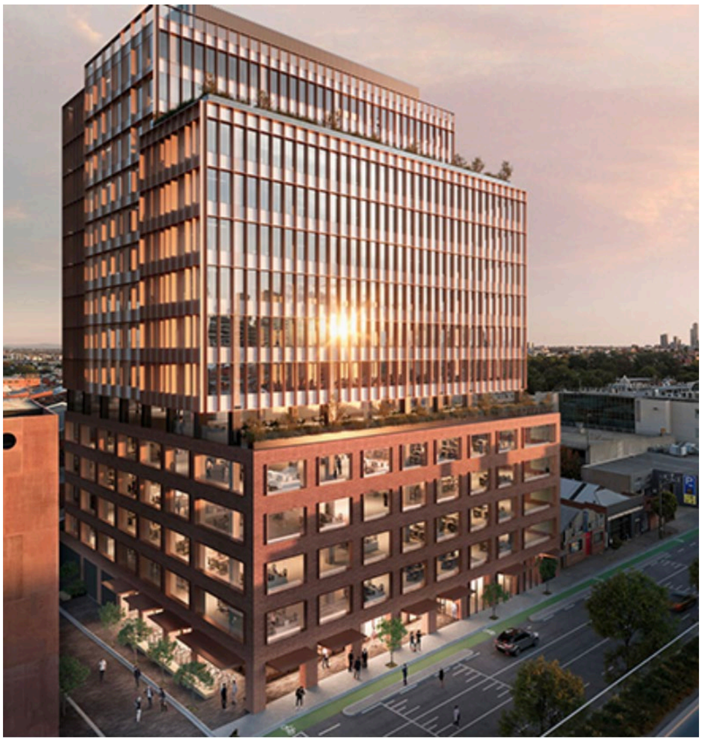


Figure 45. Melbourne's tallest timber tower, an office building in Collingwood
Source: Building Connection (2021)

Responsible environmental management

Sumitomo's products are distributed through international supply chains. They received environmental certification from the Forest Stewardship Council® and other third-party forest certifications that promote responsible forest management.

Further, Sumitomo has applied for and received chain of custody certification and EPDs for overseas products, demonstrating environmental management in the control and monitoring of its raw materials, energy and related emissions. Sumitomo uses the One Click LCA® software tool to conduct LCA for generating EPDs and plans to help other manufacturers create EPDs for their products with this tool.

Circular economy through forestry

Sumitomo has acquired a 1,000-hectare parcel of farmland in East Gippsland, Victoria, to commence an afforestation and carbon credit business in Australia. This investment will contribute to decarbonisation through the diversification of their existing ventures. In time, this will allow Sumitomo to meet the growing local demand for its supplies with the future capability to replant at this Radiata pine plantation. Sumitomo is also investigating nearby channels to directly bring engineered wood products, medium-density fibreboard and laminated veneer lumber (LVL) from their closest existing plant located in New Zealand.

Forestry products undergo a circular process. They are pre-cut to length to minimise waste. Offcuts are sent for resale. High-quality wood chips, shavings and sawdust are manufactured into particleboard or laminates. All the wood chips in New Zealand or residual matter in Japan is forwarded to biomass facilities for electricity generation, which makes factories carbon neutral. Sumitomo envisions establishing a future circular bioeconomy by rotating their wood cycle, as seen in Figure 46 below.

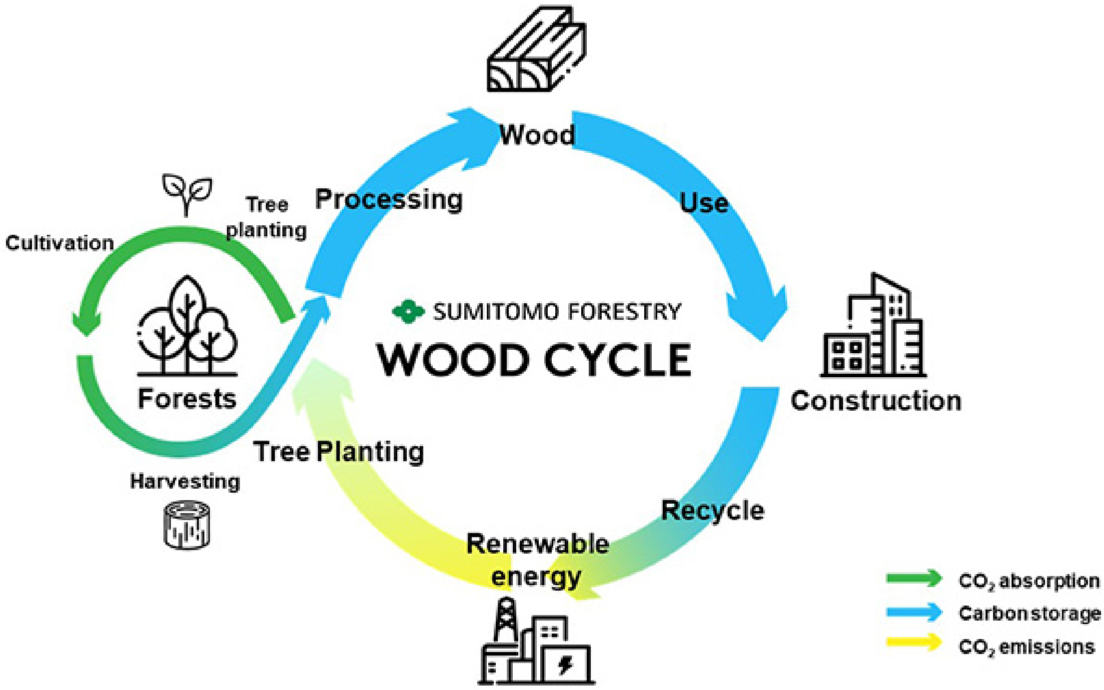


Figure 46. Cascading uses of timber
Source: Sumitomo Forestry (2024)

Obstacles to a circular economy from materials

The findings revealed several challenges in advancing CE practices, including:

- Material characteristics and contamination
- Lack of knowledge and planning
- (Re)-certification challenges
- Trust and risk aversion
- Regulatory and legal barriers
- Economic, cost and market factors
- Mindset and cultural shift

A key challenge for redirecting materials into the economy is **material characteristics**. For example, it is difficult to reuse construction ***timber*** because of the way houses are demolished. It may be possible to reuse timber if houses were deconstructed rather than demolished (thus referring to the shift from demolition to deconstruction). ***Glass*** is (presently) also difficult to dismantle from a building, although windows can be recovered from buildings and sold at second-hand markets. Glass is made from a non-renewable resource and has a lot of embedded carbon, thus a lot of energy is needed for its production as well as chemicals.

The **issue of contamination** also challenges material recirculation. Specifically, the problem of asbestos contamination in waste streams needs to be addressed. Members from waste management companies highlighted that the waste levy applies to asbestos waste even though the best solution for asbestos currently is for it to be landfilled. While the waste levy is about improving recycling, it applies to a material (asbestos) that cannot be recycled. However, as an unintended consequence, some people hide asbestos in skip bins or their bins at home rather than disposing of it correctly to avoid the landfill levy and contaminate the waste stream. Nonetheless, if the landfill levy on asbestos is lifted, some companies may be more inclined to ‘contaminate’ their waste with asbestos, because there would no longer be a deterring factor to prevent them from doing so.

Generally, there is a **lack of knowledge** regarding the stocks and flows of available materials (i.e., their volumes and sources), which makes it more difficult for stakeholders to realise effective circular planning. This gap in information makes it challenging to implement strategies for sustainable material use and reuse and to redirect material into circulation. Also, even if the materials’ location is known, **storing** them for reuse and logistics is challenging. Specialised trucks and storage space are needed. Similarly, transport costs are high.

This raises the question of who is responsible for and, therefore, who pays for the storage and transportation of materials in the CE?

Moreover, recycling materials, or any re-direction into the economy, would need **market revaluation to make sure the materials meet quality and cost criteria** to ensure the reused materials comply with structural performance requirements, such as fire, acoustic and decontamination standards and other applicable standards, to be deemed suitable for reuse. However, no best practices and standards are in place and obtaining a re-certification can also be a financial burden. On the other hand, public spaces have adopted this practice where materials do not have a major structural role.

Commercialisation at scale also remains a challenge. Industry practitioners and consumers in Australia tend to distrust the reliability and soundness of used products, driven by a risk-averse culture. This is challenging because it also means that builders, developers and designers do not want to pay more for products made from recycled materials (e.g., carpets and plastic items). Thus, this reluctance to use these products slows the CE transition.

An interview participant from **XFrame** reflected on their demountable wall solutions from the cost perspective and proposed sufficient justification for its price. Their demountable wall solutions come with a cost premium, approximately *‘10 to 15% over conventional methods.’* This often leads to discussions about whether the additional expense is justified and, in some cases, can result in the demountable option *‘get value engineered out.’* However, these solutions offer significant long-term benefits. The speed of installation is a key factor, as demountable walls can be installed *‘much faster than the conventional approach’,* which translates to savings in project timelines and allows for quicker reopening of spaces. In addition, because these solutions are prefabricated, they come with a fixed price, reducing the unpredictability of costs and lowering overheads related to project management. Despite the initial higher cost, the efficiency and predictability of demountable walls make them an attractive long-term investment.

Further, **varying laws** across states complicate the transport and reuse of waste materials (e.g., different types of timber). For example, some companies assume all treated timber contains the chemical preservative CCA instead of the safer form of alkaline copper quaternary (ACQ), so it is difficult to understand the potential for redirection now or in the future because the material may no longer be resilient **(Mayflower dba Xlam/Hyne timber)**.

Another issue emerged regarding the **container deposit schemes**. Although they are providing some feedstock for reprocessing, there are limited onshore advanced remanufacturing capabilities and facilities are unavailable for certain materials like aluminium (which has to be exported, e.g., to South Korea) or liquid paperboard. However, PET reprocessing factories have been set up since the export ban for unprocessed plastics was imposed. In addition, advancements in liquid paperboard and industrial fibreboard for building applications are underway, further driving innovation in sustainable construction materials. The market requires growth to make offtake viable for new recyclers in those areas. The container deposit scheme facilities around Australia resell goods through an auction portal to limited recyclers. Nonetheless, a collection that only leads to stockpiling is a risk that must be managed, as seen with the Red Cycle’s program collapse to redistribute plastic bags/soft plastics (Vedelago, 2022).

Recommendations of materials

Several key recommendations were proposed to promote the CE, specifically, the redirection of materials. **Contracts** could address the potential use of recovered or recycled materials, ensuring awareness and that a market is established for reused resources and reducing waste. Although some companies have already started including a clause in contracts that allows for alternative products, signalling this to designers, these are not general company policies **(GHD)**. This would encourage demolition companies to extract, retrieve and test materials for potential contamination.

In addition, while EPDs might be helpful for battling greenwashing, given the expenses and the fear of being caught in greenwashing, they lead to recycled content not being declared (also called 'brownwashing'). Therefore, products may be partially made of recycled materials unknown to the buyer, e.g., steel, aggregates and plasterboard. This is why it would be beneficial to factor these costs into their budgets, although doing so would make their products more expensive. This shows that existing standards and the lack of compliance can sometimes lead to unintended outcomes. The financial impacts on health and well-being are also often overlooked, lagging behind other considerations. This aligns with the general lack of social value consideration of circular practices.

Encouraging **waterproof and bushfire-resistant** materials can help mitigate the effects of natural disasters and enhance climate resilience, protecting against termites and condensation where applicable. These are particularly relevant in the Australian context. Moreover, developing easier methods for separating composite materials will facilitate their reuse and recycling.

Further, the **Australia Sustainable Built Environment Council** represents multiple peak bodies in the built environment. They look at **embodied carbon** as a first step to embed into policy, understand the provenance of materials and learn how to achieve a more circular mindset. Australia needs to disincentivise traditional practices to adopt more waste diversion, as exemplified by Lendlease's Martin Place project, which used GECA-certified C&D waste services and recovered a minimum of 90% of materials from landfills.

The findings point toward both the carrot and the stick approaches.

To become more competitive, reused, recovered and recycled materials must be **re-valued**. There should be incentives introduced to promote urban mining to recover aluminium, glass and other materials from companies that deal with those materials. However, penalties for sending materials to landfills (i.e., waste levies) may have to be resorted to if better sorting and collection are implemented without realising the aspired returns. Similarly, conducting cost-benefit analyses of the long-term environmental and social costs of *not being proactive* can make a business case for accelerating change for other types of projects.

Nonetheless, it is important to note that while waste management companies already extract all materials from construction waste that can be reused or recycled at a high level, there might not be sufficient recycled materials available to meet all industry needs. This warrants careful assessment of the extent to which recycled content should be mandated and required and suggests a transition to CE practices while operating business as usual. In addition, the focus needs to be urgently shifted to the reliance on the extremely high amount of raw/virgin material used in the building and construction sector. The most impactful strategy is to reduce the need for raw materials and use materials more efficiently. In other words, use materials as efficiently as possible and design out not just waste but overconsumption. Overconsumption of raw materials needs to be designed-out to safeguard our planetary boundaries.

Another potential and emerging solution is the adoption of **material passports**, which are digital documents or databases that contain comprehensive information about the materials used in construction, including procurement, reuse and recyclability information. These are highly significant in transitioning to the CE, allowing a better understanding of provenance and pathways to use. Adopting material passports is a relatively new practice, particularly referenced in European initiatives. Further details about how these material passports are supported by technological advancement are found in the Technology section of this report.

Case study of material selection: Holcim

Holcim is a leading supplier of readymix concrete, concrete pipe and aggregates. In 2019, they were the first supplier in Australia to release an EPD with third-party certification by the Australian eco-label, GECAabout their ViroDecs™ ready-mix concrete product. Importantly, this EPD showed its global warming potential and other environmental impacts, something that could previously only be estimated.

EPD information supports customers in making better-informed choices and provides greater transparency for agencies like the Infrastructure Sustainability Council rating scheme, which is unique to Australia. Moreover, Holcim could apply the recognition from EPDs to earn points for a Green Star rating with the GBCA.

Holcim also introduced innovation in its product lines with supplementary cementitious materials of fly ash and slag which are waste products from coal-fired power stations and steelworks Substitution of Portland cement by fly ash and slag reduces the embodied carbon in cement. In addition, on construction sites, Holcim collects wastewater from the process of washing trucks for use in wastewater management systems. These stocks are fed into manufacturing concrete in a closed-loop process. Any residual water is captured again at building sites along with rainwater. Holcim monitors its monthly water usage to assess system performance.

Today, concrete suppliers aiming to achieve comparable value are increasingly releasing their EPDs and implementing similar modifications to their product lines. These efforts contribute to reporting Scope 3 emissions, a critical consideration given that concrete is a major contributor to carbon emissions. During this process, the LCA data enhances clarity and effectiveness in evaluating products for circularity. However, it is important to note that the primary focus should be more action-focused, thus reducing Scope 3 emissions rather than solely reporting them.

There is a wealth of publicly available data capturing life cycle rates and material improvements assembled in databases for benchmarking and comparing product lines against competitors. Holcim predicts access to this information will lead to an evolution in imposing government policies, particularly regarding procurement.

Nonetheless, there is an economic downside to more circular concrete alternatives. Current waste levies and waste management practices already influence a high rate of recycling, but concrete is typically downgraded into lower-value aggregates for road base due to economic reasons. New concrete is cheaper to manufacture at $30 per metre for rebar, for instance, compared with $280 per kilo to dispose of it, whereas remanufacturing requires more cement to be added for strength and more energy, translating into higher embodied carbon.

Research and development

Holcim has been undertaking initiatives to investigate potential methods of reuse. They spent seven years in Australia researching ways to recycle and convert concrete aggregate and CO_2 into higher-standard concrete. This process is not financially feasible in Australia, whereas Europe has policies that dictate that 100% of building materials must be recycled. Technology for this production is available overseas and it allows larger quantities of concrete to be recycled without affecting product strength.

Holcim is enacting other transformations across international markets. The Swiss Federal Institute of Technology (ETH Zurich) and Holcim introduced a lightweight flooring system with an 80% lower carbon footprint than traditional structures without compromising performance. The sustainability of the floor solution is driven by smart design, utilising 50% less materials in their ECOPact Plus concrete that offers 33% lower carbon compared with conventional pure Portland cement. Further, they advance circularity using Holcim's **ECOPlanet cement**, which contains 20% recycled C&D

waste. Because traditional floor slabs in reinforced concrete account for 40% of the concrete mass of medium-rise buildings and need embedded steel reinforcement, combining smart design with these products progresses sustainable construction at scale.

Carbon capture utilisation and storage is another lever to accelerate decarbonisation. Holcim has six full-scale projects in execution and is committed to capturing 5 million tonnes of CO_2 annually to produce 8 million tonnes of their ECOPlanet Zero fully decarbonised cement.

In early 2024, Holcim was working in Australia to meet customer demand for low-carbon concrete by sourcing fly ash and slag admixtures that reduce embodied carbon by 30% and meet performance requirements for hardening and safety in Australia. Depending on the application, their product has the potential to reach higher savings of up to 60 or 70%, but they guarantee at least 30%. Moreover, Holcim sources high-quality by-products of fly ash from coal combustion in power stations from various locations around Australia and obtains slag from steelworks in Port Kembla, NSW. As supplies of fly ash dwindle with coal-fired plant closures, increased supplies may have to be imported from Japan to meet the higher building demand.

Nonetheless, Holcim endeavours to keep things local and reduce transport emissions by capitalising on using high amounts of renewable energy to produce cement within its Australian plants. For instance, plants in Tasmania run on 100% wind power and hydroelectricity and those in SA are projected to reach 85% by 2025-26. To fuel the cement kilns, 20% of wood chips are added to blast furnaces.

Industry advocacy and future circularity

Holcim's networks with peak industry bodies, including **MECLA** and **GECA**, in ongoing efforts to advance change, are complemented by setting higher industry standards and raising awareness of the levels of impact of cement products by certifying their management systems and quality control processes. Although the initial costs for an EPD are steep at $20,000, Holcim feels it is justified because they provide a depth of data that is unparalleled and is the way of the future. Their EPDs are based on 47 data groupings that represent over 4,000 different cement mixes and increase to 147 data sets for plant-mixed cement. They strive to group special classes for buildings and infrastructures that are unique and difficult to quantify.

Importantly, this information drives behaviour change across the value supply of the life cycle assessment of lower-carbon materials.

Holcim is poised for updates such as attaching digital product labelling with QR codes or RFID tags to materials for easier product tracking to prolong their life cycles should government policies mandate change to build the business cases. Industry breakthroughs to lower the usage of concrete have been implemented by recycling different waste products, e.g., inserting steel fibres and installing waffle pods of polystyrene blocks that are laid as void fillers in concrete slabs. Nonetheless, it makes the concrete unrecyclable, which underlines that there are trade-offs with these processes. New technologies will facilitate future change in manufacturing with more waste materials. Experimentation is being conducted to turn certain types of clay, e.g., kaolinite content, into cement or to utilise less desirable bottom ash by-products from coal-fired power stations.

In addition, Holcim North America has introduced ECOAsh, a Type F fly ash reclaimed from landfills located within its Lafarge Western Canada operations. Type F is the largest market segment and the global fly ash market was valued at USD 13.24 billion in 2023 and is projected to grow from USD 14.02 billion in 2024 to USD 23.19 billion by 2032. This is a compound annual growth rate of 6.4% during the forecast period. As market growth escalates attributed to greater building and road construction, addressing challenges related to sourcing reliable access to fly ash prompts the exploration of harvesting and beneficiating supplies from urban or landfill mining.

Life cycle (sustainability) assessment

Any new CE principle or strategy needs to undergo environmental, technical and social assessments. They rely on feasibility and standards to ensure the structural role of construction elements and materials.

Building adaptation and future use will rely on enhanced/smarter energy and water performance, which are evaluated in feasibility studies from small to large precincts and with a significant emphasis on the procurement processes **(Aurecon)**. Similarly, the reuse of existing materials depends on the testing and preparation process of the recovered material to ensure the safety of products. In some examples, reference was made to analytical tools that assist in monitoring heat mitigation and enable companies to be well-equipped and more resilient in climate change events.

LCA is a method to model the environmental impact and efficiency of products and materials throughout their life cycle. Environmental impact categories are: acidification, climate change, ecotoxicity (freshwater), eutrophication, human toxicity, ionising radiation (human health), land use, ozone depletion, particulate matter, photochemical ozone formation (human health), resource use (biotic and abiotic) and water use. An LCA needs to include all of the above-mentioned impact categories. If only the impact category of climate change is addressed, the assessment is a carbon footprint assessment and ignores other important impact categories.

Many participants talked about the value of carrying out LCAs on products and services to have a record of their environmental impacts and performance over time. For example, information demonstrating the life cycle of carbon emissions, among other environmental impact categories, provides good guidance for investment decision-making to enable more sustainable procurement. Some companies started doing whole-of-life carbon accounting (i.e., carbon footprint) to track emissions over the whole life cycle **(Skidmore, Owings & Merrill)**.

LCAs rely on high-quality data (quality and quantity) and data sets that are current and specific to the region. Unfortunately, there are only limited LCA data sets available for Australia. Therefore, data sets from other regions need to be used, which lowers the quality of the LCA results. These limitations need to be clearly stated in the LCA reports. It goes without saying that it is paramount to develop high quality and current data sets for Australia and keep them up to date.

Certification schemes are transitioning towards material reuse (*authors' note: at the time of this report*). A GBCA officer highlighted that the ***NABERS Accelerator tool*** will make LCA a mandatory requirement and will introduce an embodied carbon metric that scores material reuse as net zero emissions. This development is expected to drive significant change within the NABERS program. However, it is important to acknowledge that the high cost of LCAs could serve as a deterrent. In addition, there is a risk that some companies may misrepresent materials as recovered when they are actually virgin. To address this potential issue, integrating safeguard mechanisms through potential third-party assessment could be beneficial.

Building upon LCAs, there is an increasing interest in incorporating ***EPDs***, which are standardised documents that provide transparent and comparable information about the environmental impacts of products throughout their life cycle. They follow specific international standards, such as ISO 14025 and typically include data on various environmental impact categories, such as resource consumption, energy use, air, water and soil emissions and waste generation. EPDs examine the environmental impacts of all stages of a product's life, from raw material extraction, production and use to disposal or recycling. A representative from the NT Government suggested that disclosing the life cycle data of supplies embedded in EPDs when submitting a project tender communicates that builders intend to purchase more responsible products.

Global steel supplier and manufacturer **BlueScope Steel** has been developing EPDs with integrated LCA data on their product lines. While undergoing all the stages to secure LCAs and EPDs is a complex process, they recognise their value. They acknowledged that a lot more manufacturers are now engaged in carrying out analyses to produce EPDs in a fairly consistent manner. Further, BlueScope Steel is focused on making its materials as durable as possible and they are investigating how structural steel, at post-consumption, might be reused in the future. Currently, an overseas manufacturer is testing and preparing steel beams for reuse and BlueScope Steel is observing this progress to consider how this option might be implemented in Australia in the future. BlueScope contends that creating this opportunity will only be possible if a steel manufacturer company has a database of what material is available and can assess what standards it complies with. In addition, according to BlueScope Steel, while there might not be enough market demand or interest in making this service available in Australia, they want to explore these options should regulations change to support the reuse of materials.

According to a certifier, BlueScope Steel's requirements are well-understood in the industry and effective practices are followed. However, it was disclosed that many light gauge steels are imported from overseas and *'a lot of them are not suitable for the Australian environment.'* These imported steels typically have coatings with a lifespan of only five years, whereas Australian standards require a 50-year design life. The steel grades are also lower than those used domestically, affecting their structural performance.

There is an integrated effort to embed circularity principles in rating tools and government-led requirements, reflecting a commitment to sustainability in construction practices.

Therefore, the role of standards and requirements is especially relevant in resource requirements or in material selection. It is often realised by using LCAs and EPDs but the quality of LCAs needs to be improved. This also involves adhering to cement, concrete and steel standards, focusing on continuous improvement to become more circular. Another key aspect is the consideration and assessment of embodied carbon in construction and the overall amount of materials used. Initiatives include recycled and low-embodied carbon materials and sustainable procurement strategies to meet net-zero goals **(dsquared consulting)**.

> *'There is always room to improve that and make them more circular. But we currently have companies certified under construction and demolition waste services for buildings. We have infra build under our steel standard. We have cement and concrete standards. We have waste collection services.* ***There is absolutely the role of any standard****, whether it is GECA or someone else's, that you want to certify against, which is* ***that balance between best practice from a science perspective, but then it also has to be something that the manufacturers can achieve****. And then pushing that, it has to always be* ***continuously improving****.' (Sydney workshop)*

> *'We work on providing sustainable procurement and* ***looking at options for embedding recycled content, log embodied emission materials in both building projects*** *as well as procurement pathway.' (Adelaide workshop)*

Introducing initiatives like **Green Star Homes** reflects a growing interest in high-standard construction methods and encourages the adoption of circular construction practices. This indicates a shift towards greater awareness and integration of CE principles within the construction industry, signalling a positive direction for sustainable building practices. The shift towards prioritising circular credentials in procurement processes shows a broader trend towards rewarding sustainability and encouraging businesses to align with circular principles to remain competitive in the market.

> *'It is an interesting space with Green Star Homes coming out and knowing that there is* ***more appetite for buildings that are made to the highest levels of standards****. It is interesting in terms of building knowledge about circular construction and building.' (Sydney workshop)*

Nonetheless, the construction industry faces several significant challenges in adopting circular practices.

The **number of (requested) reports** addressing circularity or sustainability is increasing (almost to an unmanageable level). The number of reports should be limited and be focused on contributing to achieving better outcomes for circular economy and sustainability.

'I am always getting asked to produce more and more reports, so I am always just trying to work out which reports get us to the better outcomes we are looking for and what is just additional information.' (Waste Management Company II interview)

Another major issue is the **lack of design for disassembly**, which complicates recycling and reuse efforts at the end-of-life of products. In addition, there is a notable lack of data on carbon emissions and embedded carbon, making it difficult to provide accurate carbon footprint assessments. Although it was outlined previously that EPDs could provide a more consistent approach to incorporating circular design, a key issue is the high cost of obtaining EPDs or Product Environmental Footprints (PEFs) to demonstrate compliance **(Cumulus Studio)**. As a result, many companies—especially SMEs, who have remarkably fewer resources than larger corporations—do not produce EPDs as they are too expensive.

'We don't have the budget to go out and get that expert report and get it updated every year.' (Waste management company II)

Furthermore, as an underlying topic in the CE transition, the **required behaviour change** presents a significant challenge, because stakeholders often resist change. These issues collectively highlight the need for a more integrated and accessible approach to sustainability in the industry, because all stakeholders across the supply chain should aim to adhere to the same principles. Builders, in particular, should commit to driving these processes at construction sites.

Technology

Advanced technologies transform the design, tracking and management of materials and waste streams. They play a critical role in the construction and building industry to implement more sustainable and circular practices.

Depending on the technology maturity, the workshops and interviews presented examples from the most basic use of Excel spreadsheets to the more advanced use of BIM and IoT-enabled tracking devices for engineering, advanced manufacturing or integrated management systems to catapult circularity.

BIM is a smart data system that can enhance construction documentation by providing a higher level of detail of all material and product characteristics. Programs like ***Revit*** (a fully coordinated model and the standard smart data BIM program used by **Skookum Building & Design**) or ***Rhino3D*** (an open-source software used by **XFrame**) have emerged as pivotal tools to facilitate the digital analysis of planning. For instance, Rhino's one-time payment model can be attractive for small companies:

'Rhino is unusual in the sense that it does not have an annual subscription. It is a one-off payment.' (XFrame interview).

Many architects, engineers, contractors and consultants shared examples of their use of Revit because it enhances collaboration, streamlines workflows and improves project efficiency. BIM facilitates the storage of comprehensive information from every part of a building, aiding in modifications, repurposing, or decommissioning by maintaining detailed material inventories. As such, BIM can serve to include circularity information, too. Participants commented on BIM's benefits as follows:

*'Should you make any changes to the structure or repurpose it or decommission it, then **you've got all the materials stored**.' (Brisbane workshop)*

*'This particular package [Rhino3D] seems to be the **best balance of manufacturing-based tools and architectural spatial tools**. What the third factor was, we could write software into very easily and so for us to be able to develop our own like workflow software-based workflow inside of it.' (XFrame interview)*

> *'What our software does is it looks at a plan, says how many standard X frame things can I fit in this? And so that's the **translation phase from generic design to standardised circular design**.' (XFrame interview)*

Design is a key enabler in CE—BIM and digital twins are the most common technologies that support design strategies.

Particularly in the design phase, design drawings and 3D prototype models of finished structures within BIM allow companies to compare structure components and capture carbon output, energy and house temperature for quality control (**Arup; Aurecon; Light House Architecture & Science; Northern Edge Studios**). While data has been previously used to enhance quality control rather than the CE, these models can be adapted to sustainability and circularity targets (**GHD**). For instance, they can help evaluate costs and energy ratings, making materials like steel more tangible and traceable and facilitating fault protection, end-of-life and ongoing maintenance with the ability to model different options and scenarios. For example, the **building in King Street (Brisbane)**, where **Aurecon** is based, uses a digital twin and all the systems are on BIM.

BIM can also improve the industry's carbon accounting capabilities and provide feedback on the embodied carbon and materials used.

Most architects create models with a backend tag and codes linked to geometry and assembly. This linkage helps approximate the embodied carbon for each component. In particular, structural steel is more finite and traceable than other building components, allowing for a better understanding of its origin. This traceability enables companies to more accurately assess the carbon impacts of buildings over time and implement necessary changes. The process is more challenging for other building elements, but companies strive to apply the same principles to enhance our understanding of their carbon footprints.

For example, a collective of architects, designers, engineers and planners wrote a **'carbon loop' program in Revit** to track GHG emissions. Their structural engineers can trace steel better than other materials for future changes. While it is not mandated in a national framework, **NABERS** is developing an embodied carbon tool to improve the understanding of emissions factors. **Taylor Thomson Whitting**, an engineering consultancy, created a BIM carbon calculator to aid in decision-making regarding designs and tracking carbon.

In theory, drawings and specifications provide the intent of how to build, *but in practice*, builders often deviate from plans, such as placing pipes in different locations.

However, one challenge in using BIM is ensuring that builders comply with the specifications and construct projects as designed. The lack of adherence to original designs, drawings and specifications often results in discrepancies between the design and the actual build. If builders do not adhere to the BIM plans, valuable data and design information are effectively wasted. This is particularly problematic if feedback from the construction site is not communicated to the design team and the opportunity to learn and improve is lost. The importance of quality data—or lack thereof—was endorsed by another participant, explaining that although BIM has been established for some time, its adoption is limited because it requires the integration of extensive and detailed data, which can be challenging for many users.

> *'Building Information Modelling (BIM) is something that's been around for a while, but not many people use it because it is a lot of information that needs to go in there.' (Australian Circular Economy Hub interview)*

Participants recommended that designers and builders set up a feedback loop. As such, an information feedback loop, an updated BIM and accurate **as-built documentation** are crucial for enhancing the sustainability and accuracy of future designs. The more detailed and accurate this communication between builders and designers, the better the data can be utilised to refine and improve subsequent projects, leading to progressively more precise and sustainable construction practices. The founder of a circular construction technology company suggested developing database solutions where all project actors can manage, share and track data.

> *'Have databases that show where assets have been deployed to that show, like the life register of a product or a solution where it was not made, where it was like refabricated or adjusted or installed, and who installed it? Where can that be recovered?' (XFrame interview)*

Above all, participants stressed that it is critical to maintain accurate construction records for circularity. Any alterations from the original plans should be transferred to the plans in a BIM and digital twin system. That will allow all stakeholders to understand a site's design, manage and monitor costs better, oversee the performance of an asset, identify its potential faults and make better-informed decisions about maintenance in the future. However, this level of precision and adherence is not yet a standard practice.

While smaller companies may not have the same manpower or funding to deploy sophisticated technology in digital engineering, for example, they can still pursue greener construction techniques. As mentioned, smaller builders can be found across Australian cities, regions and rural areas who will build passive homes (as a key design strategy).

Digital twins are another transformative technology that enables a CE in the building industry. As one of the participants explained*: 'we design twice and build once'*. Digital twins provide a digital layer or assets of finished structures, including land use and building assets (**BlueScope Steel, CSIRO**). Similar to BIM, capturing and storing information on material flows in digital twins provides evidence for future decision-making while minimising disruption to residents. The data is shared and stored on the **cloud** among multiple facility owners to optimise performance by connecting renewable sources and energy efficiency data with maintenance regimes and fault protection.

Digital twins inspire advancements in life cycle assessment, maintenance and performance metrics by enabling real-time monitoring of components.

Digital twins are not just for compliance but also for user experience. They are **tested under different scenarios** and can be applied to a digital twin. This includes everything from external forces and stresses on the system to changes to the operating environment for those buildings. However, digital twins often integrate third-party software to automate multi-systems, which can be a costly investment. Thus, it is mostly adopted by tier-one projects or owner-occupiers of large buildings.

Digital twins can also facilitate the use of **prefabricated recycled materials** (off-site) which are then brought to the site, which is also a key circular design element. A reference was made to a fully timber building, including six floors, which incorporated recycled materials (as far as practicable) and minimised the amount of materials. An emerging trend involves leaving ducting exposed. This feature reduces the amount of materials needed in the building and showcases the structure itself.

Another case is the **XFrame's demountable wall solution** and the technology they use in the process. This includes detailed specifications down to the screws. According to the participant:

> *'It is a **digital relationship to the physical thing** being built right throughout the journey of it getting made on a project-by-project basis… It is essentially a digital twin model, but it is made for fabrication. What is the length of the screw? Where does it go?' (XFrame interview)*

Another example is **Schindler's lifts**. If a Schindler lift is in a building, there is an opportunity to interface with the manufacturer to enhance data collection and live monitoring for maintenance purposes. Therefore, real-time data from the lift can be used for ongoing maintenance and performance optimisation. There is an aspiration to move towards this integration and data utilisation level, representing a significant step towards more advanced and efficient building management.

references were also made to carbon-related initiatives. For example, large engineering firms, like **Mott McDonald**, developed digital twin systems for their large infrastructure projects around managing embodied carbon. One of the examples on the MECLA website is a presentation from **McDonald's on their Kidston pumped hydro facility** in north Queensland. **Carbon Twin** is an interactive platform built on the Unity gaming platform for infrastructure projects to manage embodied carbon. They have created a digital solutions life cycle platform, **Moata**, for enhanced project delivery, asset performance and social and environmental outcomes. Also presented on the MECLA website is the program **Carbon Trace**, which tracks carbon at a residential scale. **Grenville Architectural Construct** also designed a carbon tracker tool for residences.

Similarly, **Stanwell Corporation** is determining how to track the flows of phosphorus and ammonia in sewage systems through digital twinning to capture and store that information in a network rather than BIM. After separating these elements to meet compliance with discharge targets under their license, they want to capitalise on reselling these products when they become scarce and their value increases. Biosolids are reused on land after being released from a wastewater treatment plant.

Nonetheless, **interoperability with other systems** remains a key limitation. The effective use of digital twins relies on other digital technologies and it is important to collect data, use the information properly and use automated and intertwined projects. Further, it remains a barrier, because software vendors, programs and states differ in how they wish to receive data and some providers have proprietary systems, which makes it hard to share with other parts of the organisation. This is why open-source software is popular.

Tracking and following materials along the value chain is a key characteristic of the CE and is important to extend the life cycle and maintain existing products and materials.

Construction firms also rely on simpler and more sophisticated tools for a CE. For example, a demolition and civil contractor uses **Excel** to track waste and material streams, ensuring companies have access to records and streamlined processes. Monitoring systems track energy consumption and temperature in buildings, providing valuable data for assessing design efficiency and informing future projects.

In this example, the company tracks materials that are removed from demolition projects. In a large Excel spreadsheet, they record the quantity and types of materials, allowing them to separate and decide which materials to recycle and recover. In particular, they record the quantity and types of materials in the spreadsheet to understand how much concrete, for example, can be crushed and redirected for new civil works projects to repurpose the material. For the **Level Crossing Removal Project** in Melbourne (to remove 110 dangerous and congested level crossings across the city by 2030), partners used a simple **SharePoint database** to record and store information on 62 materials and their recycled content (63%). This approach, while rudimentary, provides the company with a basic understanding of its different waste streams and where they go. This example points to the critical role of data in the construction sector and its circularity.

Numerous databases exist, each containing unique **data** features. References were made using EPDs and LCA data. This area has been a focus for quite some time and is increasingly being incorporated into large models. Some companies even perform statistical analyses on the EPD data rather than simply using it as is. Despite the complexity, the amount of data, particularly in the building sector, is growing as more manufacturers produce EPDs. These EPDs are becoming more consistent in their development and presentation. Large engineering companies have invented interactive LCA platforms for infrabuilds that enhance project delivery, asset performance and social and environmental outcomes.

Engaging a **resource recovery auditor** to value the products and materials removed from the sites will be important to enable a CE.

This could enable the shift from demolition to deconstruction and identify ways to reuse or resell them.

For example, **BlueScope Steel** underlined that when establishing such datasets, it is important to decide which key parameters need to be recorded and communicated. This also required understanding which stakeholders need access to this information and determining the data's relevance to each group. Therefore, this process is essential to understanding how information flows throughout the value chain. This is an ongoing work area and the company aims to optimise the data management and communication strategies.

Blockchain technology and IoT also have the potential to test the provenance of materials and offer assurance regarding their origins. A Sydney workshop participant discussed the research undertaken at Western Sydney University on using a QR code-enabled blockchain system to track and create a marketplace for reusable materials. It highlights the potential of the technology but also underlines the need for more research in the field. Please see the ***Case study of IoT and glass recycling: VENTORA Glass*** below.

QR codes are another example being explored for tracking materials, like steel and concrete, to facilitate future design, maintenance, repair and disassembly. This technology could significantly enhance design documentation and potentially provide a comprehensive history of materials. For example, **Cumulus Studio** discussed their university, hospital, or large-scale project, particularly as it will be for owner-occupiers who will request a higher level of detail in a model. Although they are very costly, detailed 3D models can be used for building maintenance. Every part has a traceable QR code, which is useful for deconstruction to extend life cycles, although the model must be updated to its as-built state, which is uncommon.

While there could be potential in tracking every single item in the construction process, it could be problematic and may not be feasible or add value.

An XFrame representative reflected on the role of material passport:

> *'We would love to do material passports, but we just **cannot see a practical way of implementing**. Each part, each panel [demountable wall] has about 20 or 30 parts in it. Do we have the tag for each part that then makes up the panel that then makes up the building?'*

This level of detail can become overwhelmingly complex and resource intensive. Instead, focusing on panel-level information is more practical and effective. *'We think the panel level is about right, like if we can tell a customer you've got a panel and we know what's in the panel, we're not going to independently tag every component.'* This approach simplifies the process while providing essential information about the construction elements.

The concept of a **material passport** is gaining traction but, while its theoretical benefits are acknowledged, its practical implementation is still nascent in Australia. This tool links designs directly to material tracking, offering potential yet unrealised benefits in the industry, such as reusability and a more efficient use of the waste hierarchy. In addition, reference was made to material passports' ability to support reporting and the job of insurers and investors by providing some certainty around the provenance of materials and their future value (see more on real-time visibility opportunities in the **iMOVE CRC project***).

The **interoperability of systems** is crucial for the effective use of any digital assets in the CE. These systems need to be able to seamlessly collect and use data across different projects and stakeholders. Internal processes often drive technology readiness and the growing need for digital modelling specialists underlines the importance of skills and capabilities in this evolving landscape.

*__*iMOVE CRC__ – Taking Transport to the Future Faster*

*The iMOVE CRC advances the development and adoption of technologies that improve Australia's transport systems, through high impact R&D collaborations. The iMOVE CRC develops new products that provide **real-time, end-to-end visibility of the transport network.** This will result in better predictive capability, eliminate network downtime and offer scalable solutions and improve Australia's competitiveness in the global network management market.*

iMOVE CRC research programs encompass: Intelligent Transport Systems; Sustainability; Freight & Logistics; as well as Mobility.

Ultimately, optimising the operation of facilities and infrastructure would greatly benefit from **centralised data management**. Initiatives are underway to consolidate data from various sources, including multiple facility owners, into cloud-based platforms. This collective data sharing enables insights into improving operations, integrating renewables, enhancing energy efficiency, implementing maintenance regimes and enhancing fault protection measures. Centralised data management facilitates more informed decision-making and fosters continuous improvement across various aspects of facility management and infrastructure operations.

Case study of IoT and glass recycling: VENTORA Glass

VENTORA Glass is an Australian window manufacturer and supplier. They have adopted an IoT system to prevent the loss of their A-frame systems, which are used to transport windows to customers. In addition, typically, the company sends glass offcuts and other waste streams for recycling along the east coast of Australia.

IoT for tracking

VENTORA Glass purchases A-frames to load their windows on trucks and safely deliver them to customers without incurring breakage. However, when the windows are unloaded, the A-frames are frequently left at a customer's site, forwarded to a different customer, or disappear because people find them handy for storing and distributing their own goods.

It was a constant and very expensive loss as each frame costs AUD 2,000 and comes from an overseas supplier. After searching for an effective solution to manage this problem, VENTORA Glass found a company in Western Australia that sells small tracking devices for AUD 150. They bought 300 trackers, bolted them to the A-frames.

By paying a nominal subscription fee to a third-party telematics operator, VENTORA Glass can pick up the signals for all the A-frames. Staff members draw a geofence around the buildings of customers where trackers are headed and every eight hours the tracking website updates, allowing them to track the whereabouts of every frame. If one goes missing, VENTORA Glass will contact the customer where the frame was dropped off to share information about its history. When a customer discovers it might cost them AUD 2,000 to replace, VENTORA Glass always retrieves the A-frame so it can ship new products to customers without delay from both their factories in Brisbane and Melbourne. Word spread of its success rate, resulting in new purchases for the tracker supplier.

Recycling

In window factories, there are a range of different glass types used to create windows, ranging in thickness, colour and choice of lamination or non-lamination. Offcuts are trimmed to various sizes. Glass waste amounts to between six and seven tonnes per day, but glass waste is all deposited into a large skip bin for removal by a glass recycler. Because the industry is more competitive in Victoria, the recycler there will give VENTORA Glass a rebate for this waste, to grind it up and produce float glass, roof insulation, or termite barrier. In Queensland, the market is non-competitive, with only one recycler due to the high capital investment, which means that VENTORA Glass has to pay for its waste to be removed.

However, all their industrial glass waste, can be recycled. At the end of life, demolition companies send commercial windows that VENTORA Glass makes to auction houses or second-hand stores for resale and reuse. The rest of their waste streams are sent to a cost-effective waste management company, which has a high 85% resource recovery rate. By recycling a significant amount of waste, they reduce the amount that goes to landfill, thereby saving on waste levies.

Circular construction—towards a new supply chain

Achieving CE in the construction industry's supply chain requires a holistic and collaborative approach. Because CE is a 'team sport', aiming for industrial symbiosis and adopting a whole-system perspective is crucial. This system view promotes a mindset that comprehensively considers all aspects of the CE. This process involves rethinking traditional methods and fostering innovative approaches.

The findings underline that the success of any design strategy is dependent on how it unfolds in the construction phase. Lead designers and construction consultants are knowledgeable about supply chains. They can influence better buying, yet builders drive CE initiatives by placing orders and engaging with sub-contractors responsible for segregating different material waste streams. References are made to establish market demand and a takeback infrastructure, thus thinking about **circular systems**. Changing behaviour across the value chain is underpinned by early intervention, utilising a circular framework, looking at **leaders' best practices, instituting legislative change and educating consumers**. As a result, early involvement facilitates design and retrofitting processes, ensuring that circular principles are embedded from the outset. MECLA's supply chain map provides a way to visualise and improve the circularity of supply chains.

'We're never gonna do it alone.' (Sydney workshop)

For example, in developing a renewable energy pipeline **(Stanwell Corporation)**, the participants pointed to the early planning and engagement with contractors, developers and suppliers, starting from the tender phase to incorporate sustainability considerations effectively and create a genuine CE from procurement to commercial operations. For instance, material selection and production are highlighted in the procurement processes. Similarly, **GHD** provides engineering, architecture and construction services. Their water division consolidates business strategies at an early project phase to avoid duplication of services to conserve water.

*'**Early contractor involvement** from a circular framework, having every player in the room or as many as you can to design out the waste as a first principle.' (New South Wales workshop)*

Addressing disconnections in the circular economy

A significant challenge in the construction industry's transition to a CE is the existing disconnection across various process stages. It is essential to reach people outside the conventional 'bubble' of sustainability advocates to broaden the impact. Each stage of the CE in the built environment influences others, making upfront design for a CE critical for material recovery and separation. The focus needs to extend beyond just renewable energy and GHG reductions to encompass comprehensive CE principles.

Further, disconnects between policy and the NCC and between design and construction hinder progress. Builders often do not comply with the design intent, leading to discrepancies between the planned and actual structures. This gap limits the impact of choices regarding design and materials, highlighting the need for better alignment and communication.

An XFrame representative also raised the issue of disconnect with builders. While requests have been made to review material passports and similar documentation (XFrame), a challenge arises in that while the materials in a project can be accurately detailed when they leave the factory, monitoring or accounting for any changes on-site is not feasible. As the XFrame participant explained:

> *'One of the most common things that happens is we'll put our one of our ceiling systems in. The HVAC guys come through and cut holes and everything. You know they need to make a hole for the extract duct. They need to make a hole for the security camera and they need make a hole for the motion sensor.* ***And as soon as they do that, we can't classify it as a standard element because it's been tampered with or modified****.' (XFrame interview)*

On this note, the role of **feedback post-construction** was discussed, because this was important for designers to better understand the actual vs designed materials used and the waste generated on-site **(Skookum Building & Design)**. Similarly, one participant (**XFrame**) proposed a potential solution of a **'modification register'** to track such changes on-site. Therefore, the sub-contractors and builders play a key role in implementing the required designs and providing feedback once the installation occurs.

A key concept in establishing circular systems was **integrated project delivery**, because it brings together and enables architects, engineers, planners and consultants to develop circular systems. This also ties in with the importance of education and awareness in promoting sustainable design practices.

> *'There is capacity in the market to reach these circular metrics, but they need to keep improving. And that requires not just the manufacturers to change their process, but* ***the ecosystem that they're in*** *to allow that as well. Sometimes the manufacturers have done everything they can possibly do, but there needs to be those other links in the chain for that material to be picked up again or it depends on the material.' (Sydney workshop)*

Similarly, XFrame utilises a **distributed manufacturing approach** to optimise production efficiency and flexibility. By leveraging local manufacturing resources rather than relying on specialised, centralised plants, XFrame can tailor its processes to the specific needs of each project. As noted in an XFrame interview,

> *'How do we take advantage of a distributed manufacturing work? How do we make the product in a way that doesn't require us to set up specialist manufacturing plants? And so even right to this day we leverage local manufacturing depending on where the project is.'*

This strategy involves providing local manufacturers with detailed specifications, including *'how to cut the products, what our tolerances are, what are our QA methodologies.'* Such an approach minimises logistical challenges and infrastructure costs while enhancing responsiveness to project demands and local conditions. By decentralising production, XFrame achieves greater adaptability, reduces lead times and supports more sustainable manufacturing practices.

Supply chain collaborations

The circular economy is a team sport.

Collaboration within the supply chain is vital for promoting CE principles in construction and as one of the Sydney workshop participants noted: *'Circularity is a team sport'*. It requires collaboration across different sectors, including government, waste management, construction and environmental regulation. Australia faces challenges in fostering such interdisciplinary collaboration, as explained by one of the researchers and experts interviewed for this research.

> *'To me, if we are only talking to the buildings and construction people then and they're not talking to the people that are working in the waste sector and they're not talking to people in local government... we can never actually transition to where we want to go.' (Researcher and external expert interview)*

> *'Engineers and standards need to come together with planners and approvers of plans to have confidence that we can actually change the system.' (Australian Circular Economy Hub interview)*

Significant events at **MECLA** bring together different parts of the supply chain, facilitating essential conversations. These discussions cover various stages, from early contractual agreements to design considerations and adaptive reuse at the end of a project's life, ensuring that the right questions are asked to promote reuse and prevent waste. Reference was also made to **circular hubs**.

> *'If we really want to help drive this change and achieve your circular economy by 2030 vision, for example, we really need to bring everybody along, and it is that behaviour change process and circling back. It might be **different ways of engagement** and thinking about things in different ways than we have thought about. And I think that's time poor people who are both working on their business and in their business it can be very time challenging for them.' (Sydney workshop)*

> *'What is happening globally and nationally, **the concept of circular hubs is not new, but it's much more established in other parts of the world.** We're doing some research on circular economy hubs, looking at the different types that exist, whether they're micro-ones operating in a sharing library within a building, or having a community space where you might have a repair café. The social impact of this, it helps with the cost of living and gives the intergenerational opportunity of connecting. If you get to the where you have circular businesses in one place, they could form a transfer station within a whole network, becoming an ecosystem of a number of businesses.' (Peak body representative)*

It emerged from the findings that to effectively create a CE in the building industry, an **ecosystem** approach that promotes **industrial symbiosis and a whole-systems perspective** is essential. Circularity must be addressed through a holistic lens, avoiding siloed solutions that merely shift problems rather than solving them. This approach requires bringing all stakeholders together—designers, builders, policymakers and workers—to collaborate and communicate effectively, ensuring that each participant understands their role in the system. Integration of white- and blue-collar workers, fostering change management and behaviour change processes and aligning policy with CE principles through contracts and investments are crucial for driving meaningful progress.

> *'And then I think as MECLA rightly pointed out, there is a lot of work happening with some crossover and collaboration, but I feel that while there's still a lot more that needs to happen that we don't constantly have a new hub starting. We have pretty much what we need to get going. **We just need better communication as to which how we all fit in the puzzle. We all have different roles to play.**' (Sydney workshop)*

Material and information redirection channels

Supply chain collaborations enable the creation of material and information redirection channels, supporting local solutions and marketplaces for CE. Builders can negotiate with suppliers of recycled materials, considering perspectives such as embodied carbon and resource reuse. Effective communication between builders and designers about available materials and ethical considerations is essential.

Donating materials to charities, like **'Helping People Achieve'** and establishing systems for sharing or repairing products for reuse are practical steps. Examples include **Interface Carpets**, which has a take-back program at the end of their product's life and **the Waste Resource Recovery Board's** initiatives. Waste recycling associations can facilitate connecting partners along the value chain to develop viable recycled markets or promote salvage yards.

> *'Builders need to understand their impact, their footprint. This industry is under pressure now. There's enormous cost savings of not over ordering and wasting your materials. **We have material shortages everywhere.** Building case studies and showing examples where it is a cost savings—even if you don't care about the environment—it is actually a cost saving for builders.' (Peak body representative)*

One participant talked about the **Bridge Bank** example in the Netherlands, a practical example of CE principles applied to infrastructure. This system allows decommissioned bridges to be listed in a **marketplace** where other regions or councils can repurpose them. This concept emphasises resource efficiency and extends the life cycle of infrastructure components.

> *'The Bridge Bank is something that's been implemented by the Ministry of Infrastructure and Water and basically it's a case where if you've got a region or a local council that's got a bridge that they want to take out...it goes into like a marketplace of sorts.' (Australian Circular Economy Hub interview)*

However, a significant problem is the lack of market understanding and local reuse opportunities for materials like steel and tyres. The industry needs to develop new markets and improve knowledge about where materials are located and how they can be recirculated into the system. For instance, leftover materials from one project could be utilised in future projects by other businesses, but there is currently no system to facilitate this exchange.

While technology can facilitate tracing materials and information along the supply chain, a participant discussed the reluctance to adopt new technologies in certain specific tasks, with a preference for traditional signed drawings: *'Our builders love a printed PDF. That's all they want.' (XFrame interview)*. In addition, there is a notable shortage of labour and resources, making it difficult for SMEs to access and implement necessary tools and technologies.

Cost is the prime driver of supplies and it is assumed that many building products are manufactured overseas, which is cheaper and less carbon-intensive. Nonetheless, resource limitations present another significant barrier to achieving a circular supply chain in construction. Procurement issues, lack of storage for materials and insufficient space and time for handling recycled or reusable materials are common challenges. For example, the COVID-19 pandemic highlighted the vulnerability of the timber supply chain, leading to long project delays. This reliance on international supply chains has underlined the importance of **understanding the origin of materials**. In another example, birch ply from Russia faced import issues, prompting a shift towards Australian-made hoop ply.

Further, the **impact of transportation** on the CE must also be considered, particularly in remote areas like **Tasmania** or the **Northern Territory**, where transportation costs are high and the market is small. Keeping supply chains local whenever possible is crucial to reducing truck miles and the associated environmental impact. The decline of manufacturing in Australia has further complicated this issue, emphasising the need for **local solutions and responsible sourcing**. Appropriate planning is needed to forward C&D supplies and establish logistics and storage facilities for reprocessing. It is important to note that vernacular architecture is a way to minimise distance and resource expenditure, but it seems to be an exception.

> *'Everyone's part of the supply chain and reporting is starting to affect the big players at the moment, but pretty soon it's going to be down to all showing what's your footprint? Suppliers know about that reporting both here and in global perspectives.' (Peak body representative)*

Partnership across sectors

Achieving a circular supply chain in construction necessitates robust partnerships across state and local governments, private enterprises and industry stakeholders. These connections are pivotal in improving industry practices.

> *'We also do a lot a lot of engagement across industry sectors. We realise how ill-prepared or little prepared industry is and their awareness of what is happening at the forefront of the circular economy era, and where mainstream builders and even companies are part of the supply chain. They need to report on things quite soon and there's a big gap.' (Peak body representative)*

Governments play a crucial role by demonstrating and testing what is possible. Partnerships with organisations such as the **Green Building Council of Australia (GBCA)** and **Green Industries South Australia (GISA)** have led to the creation of a CE guide for the built environment.

Collaborative efforts include Logan City Council's work with BlockTexx, Engineers Australia and using the Green Star rating system for building and usage standards. The **Global Environmental Choice Alliance (GECA)** advocates for federal, state and city policies, participating in better building partnerships and CE working groups. As one of the GBCA officers explained:

> *'GBCA is a member-based organisation of around 650 members. It's one of Australia's biggest property developers, about 20% of Australian Stock Exchange Top 100 members. We've got a lot of local councils, I think there's 39, but they cover about 40% of the Australian population (most of the big local councils are members), and then we've got a lot of consultants—architects and designers, engineers, landscape architects, interior designers, planners as well as other levels of government and universities. We've got 22 university members.' (GBCA interview)*

> *'We work across a number of areas, whether that is with research, PhDs, and other kinds of innovation.' (Peak body representative)*

Suggestions from participants also include fostering **coopetition**, where industries collaborate rather than compete and focus on the practical application of CE concepts rather than purely theoretical models. The need for ongoing commitment and a coalition of willing participants is stressed.

> *'Don't compete. You can still hold on to your IP. You know there is a term that we started to use when Jacqueline [Jacqueline Cramer] was here and that is coopetition.' (Researcher and external expert interview)*

However, the construction industry is often scattered, with projects across various geographical locations and stakeholders involved. This fragmentation can hinder cohesive efforts towards CE practices.

For instance, developers, energy buyers and project owners may not always align their goals and practices, making it challenging to implement uniform circular strategies across all projects. Similarly, major metropolitan areas have different needs and resources than remote or rural locations. Tailored approaches are necessary to address these geographical disparities and ensure that CE practices are effectively implemented across all regions.

Many individual and large firms are taking their own innovative approaches as well. Entering the SA Government competition, the **Zero Carbon Challenge**, architect Mark Thomas and Oli Scholz from Goodhouse partnered with other building industry and academic members to come up with a smart living system. It factored in carbon accounting, embodied and operational energy, materials and methods on a budget to create a sustainable structure that was on budget and conducive to its environment.

Making the construction industry's supply chain more circular involves a multifaceted approach that includes holistic thinking, stakeholder collaboration, addressing material and information redirection gaps, balancing local and international supply chains and rethinking engagement strategies. The industry can make significant strides towards sustainability and a CE by fostering better communication, developing local markets and aligning policies and practices. Various additional factors can enable these processes.

Key enablers

Additional enablers, such as policies and regulations mandating sustainable practices, educational programs training professionals in sustainable maintenance techniques, certification systems recognising green buildings and investments in innovative CE strategies, can support a CE in construction. These aspects collectively contribute to buildings' long-term sustainability and resilience and support the shift to a CE.

Education and training

Participants believed that **education and training on CE** would influence its wider adoption and inspire greater confidence. To date, courses in the CE are predominantly offered to interested students at a select but a growing number of tertiary institutions. One of the Adelaide workshop participants recently graduated and earned a PhD on the topic of design, construction and demolition waste and is now working in the CE team of the engineering firm **Aurecon**. Other examples are presented in our market review in Table 8.

> *'There's much more support needed for education and training. And I know the industry is obviously under immense pressure. No one can take on anything else, but it means they're going to be far behind when they have to be ready. If they don't have the skills, and if their staff hasn't been trained to work with these new processes and procedures that need to be in place since we're still arguing about 'why bother with double glazing', it's going to be a really slow process.' (Peak body representative)*

> *'You need to provide ongoing education and training. There needs to be time made for developing those future skills that's going to be needed. And it needs to be built in across the board, whether it is trade type training or within tertiary education and embedded in education at all levels.' (Peak body representative)*

Many professional bodies, such as **Engineers Australia** or the **Australian Institute of Architecture**, run continuing professional development seminars for their members or host public events to capture more interest in the CE. The **Adelaide Sustainable Business Network (ASBN)** is a locally based, not-for-profit business that brings together a diverse range of professionals and community groups through events, lectures, workshops and projects to advocate for the uptake of sustainable and ecologically beneficial practices across the builders and affiliated tradespeople.

In addition, the **Australian Circular Economy (ACE)** Hub by Planet Ark has featured a series of ***'Learnings from Europe'*** webinars on their website. Among numerous examples, they acknowledge initiatives, such as the World Circular Economy Forum, World Resource Institute PACE and Circle Economy. In May 2024, they launched the ***'Circular Economy Fundamentals'*** and decided to increase their knowledge platform to turn the webinars into a monthly educational initiative to guide more government, industry and academic subscribers on transitioning to a CE. The ACE Hub also hosts a portal and publishes a newsletter informing subscribers about CE news and case studies, which cover building alongside other circular topics. The establishment of the ACE Hub signifies a pivotal moment, marking a transition from traditional environmental campaigns to a more holistic approach that includes industry and government collaboration. The educational essence of Planet Ark was endorsed by one of the interviewees:

> *'Planet Ark's really about sort of an education platform… we have quite direct involvement with industry and with government at all three levels.' (Australian Circular Economy Hub interview)*

Another outlet that regularly offers green training classes to its members is the **GBCA**. Recently, the GBCA added a training course on responsible materials, which has garnered significant popularity. The course often reaches full capacity and maintains a waiting list of interested participants from the commercial building sector, local councils and state government agencies.

> *'In terms of responsible products, the industry is learning about it and how to implement it and how to get their products in it. We've run a few of the same master classes on circularity three times.' (GBCA interview)*

Most national institutions deliver hands-on training with specialties that cater to market trends for greater solar or passive housing to lower building operational energy costs and extend dweller comfort. Thus, tradespeople keen to learn those skills can enrol in online courses leading to certification. Builders in each state or territory must pass tests to acquire a license to operate. Although CE is not widespread among TAFE vocational training providers, the Victorian Government has introduced a new CE-focused course called *22667VIC Course in Circular Economy Practices* in July 2024.

At the university level, **RMIT**'s efforts in developing courses and integrating CE concepts into various educational programs highlight the importance of academic involvement. On this note, reference was made to the CE as an overarching theme, as well as its impact and relevance on business models, digitalisation and the transition process itself. Moreover, it was underlined that the CE transition requires a *'systemic understanding and a systematic approach' (Researcher and external expert interview).*

> *'I was instrumental in developing the first circular economy in the built environment course at RMIT... It's become quite clear to me that even when I started looking at circularity from a built environment perspective, it became very clear to me that we also need to think about business models, digitalization and just transitions.' (Researcher and external expert interview)*

One of the employees from the demolition company, **NTEX**, recommended that licensing be established for companies involved in demolition work due to its inherent dangers. The increase in individuals engaging in concrete crushing for civil works projects has improved resource recovery rates; however, the qualifications for such work need to be elevated to ensure safety and efficiency.

Besides spreading knowledge for sustainable building practices within the industry, workshop attendees emphasised that educating a broad spectrum of building owners and occupiers is crucial to fostering understanding and creating demand for circular change. According to a peak body representative:

> *'We work across a number of different initiatives in education for supporting industry to getting there. That's first by writing case studies about those who are already doing it, who already developed that by or by funding with the GBCA. That report that we did and those leading in the areas showing what is already happening.' (Peak body representative)*

A builder from Tasmania drew attention to a publicly accessible website, www.yourhome.gov.au, that foregrounds people's knowledge of better building techniques. People can buy the entire ***'Your Home'*** guide or look up information online on this database to learn how to build environmentally sustainable homes across Australia's different climate zones. This comprehensive resource covers everything from learning how to build with naturally renewable materials to selecting and using materials that can save money, reduce waste and minimise environmental impact.

There is an increasing awareness towards CE and thus, there is a need to support this transition.

A key aspect in adopting any learning outcomes remains **context-specific learning**. A peak body representative also commented on their processes to ensure it was adapted to the SA context:

> *'How can it be adapted to the Australian context and then down to the South Australian context as well, and bring everyone along? We support social enterprises that might be working in this space. A circular impact incubator that's been running for a couple of years is Collab4good. They bring people together to lead, learn, connect, and collaborate in capacity-building business programs.' (Peak body representative)*

Partnerships with the public and community organisations are crucial for knowledge sharing in the construction industry's CE. Information dissemination through journals, websites and platforms like ASBN ensures that valuable data on energy usage, retrofits and new build projects is accessible.

Resources such as the **'Green Book'** provide information on sustainability and contacts for relevant companies and demonstration projects impact practical learning and skills development. Education initiatives for clients and training courses help gradually shift mindsets towards circular practices. Engaging architecture students in circular design, thinking and design for deconstruction and modularity is also an essential strategy for fostering future industry leaders committed to sustainable practices. As the GBCA representative noted:

> *'In our member survey, we asked people what they see as the biggest challenges for the year ahead because that's a really good indication of the things that Australian markets see as important. For 2024, sustainable net zero buildings and the energy transition was number one, and circularity was number two.' (GBCA interview)*

Certification, reporting and awards

Certifications are valuable because they hold practitioners up to the standards. A Melbourne architect warned that if a builder is going to embark on a less traditional construction method, then it is prudent for practitioners to check in advance with local authorities to ensure a project can be

certified or understand the risks of trying to complete a less conventional structure (i.e., being denied an occupancy permit). It can become a costly mistake. Another architect explained:

> *'The certification holds us to that standard, which we're very happy to be held to. We find a lot of clients are interested in that.' (Architect interview)*

The study findings also revealed that states or territories may update their standards, as seen in the transition to 7-star energy efficiency under the **NCC** recommendation. This means builders must keep informed of what criteria are expected under new rules and learn to execute procedures to meet the higher standards. Although policies for higher energy efficiency are a catalyst for positive change, they can translate into extra time and costs to complete a construction project, so practitioners need to be prepared. This is related to the education and training component mentioned in the previous section.

Many different certification schemes offer different benefits (as presented in our market review), but as stated, certifications can be expensive. Nevertheless, investors, developers and building practitioners recommend certification for better building and behaviour change. Both **Jones Lang LaSalle** and **Commercial Real Estate Services** reported that tenants and buyers demand sustainable asset certification before they move into a property and several workshop participants affirmed this notion.

Green Star Buildings (of the GBCA) is arguably the largest certification program in Australia. It has a suite of rating tools. The tools shift from assessing only carbon emissions and having companies demonstrate other environmental standards to factoring in social and biodiversity criteria. As one GBCA representative explained:

> *'The rating tools are a suite of Green Star rating tools that cover all the buildings in Australia's built environment essentially, except for standalone empty, free car parks. Any commercial building that is covered under the National Construction Code can be rated. The Green Star Design and As Built rating tool has been replaced now by Green Star Buildings.' (GBCA interview)*

According to the GBCA, LCAs will become a mandatory component of the Green Building rating tool. A GBCA representative commented on LCAs and evaluated their cost implications:

> *'Members got **points for improving their embodied carbon** compared to what it would have been, and now we've ramped it up again. **Exceptional performance in Green Stars is a 30% reduction in embodied carbon**. For example, in the banning of new gas connections or upgrades to the minimum requirements in the National Construction Code, Green Star only kicks in at Australian best practice. We do a lot of advocacy work to try and encourage those people to build more sustainably and **lift minimum regulations to build more sustainably** because otherwise, we're not going to meet the Paris commitments.' (GBCA interview)*

Upcoming changes with **NABERS** will similarly move towards evaluating broader sustainability metrics. A GBCA member provided an overview of the rating tools and the relationship between **Green Star and NABERS**. Most projects using Green Star in Australia are commercial buildings or multi-unit residential developments, with around 3,500 buildings rated. NABERS, which includes assessments for energy, water, waste and indoor environment quality, is often associated with energy ratings due to its mandatory disclosure requirement for buildings over 1,000 square meters. Any building of this size must have a valid NABERS energy rating for transactions like sales or leases. Then, NABERS energy ratings are integrated into Green Star Design and As Built or Green Star Buildings. When conducting NABERS energy calculations, these contribute to the energy credits within the Green Star rating. However, Green Star encompasses much more than energy efficiency. It includes nine different categories, with energy being one of the components evaluated.

Energy modelling is still required in the newer version of **Green Star Buildings**, but it is rewarded differently due to stricter requirements than those set by NABERS. Specifically, the tool demands a 10% improvement in energy efficiency compared with the NCC and a 10% reduction in embodied carbon. Within the responsible category of Green Star Buildings, there are credits for reducing carbon and materials based on a responsible product score. Products earn this score by uploading their information into the framework of the responsible product along with their EPDs. This initiative aims to advance the market by addressing broader social impacts, such as reducing modern slavery and increasing diversity. In the future, they intend to include biodiversity impacts with new products.

GBCA also has a rating tool for fit-outs and for the operation of buildings called **Green Star Performance**. This is a holistic rating tool for the operational performance of the base building. Then, there is another new rating for **Green Communities**, which is a precinct-wide rating tool. Reflecting on the role of fit-outs, the GBCA representative explained that in the context of the CE, fit-outs are a big component.

> *'While the base building might be standing for 50 years, the fit-out is probably going to be ripped out in between 5 and 10 years. Those are the four tools that together cover the commercial built environment.' (GBCA interview)*

For individual research reports, the GBCA focuses on topics that interest the market and participates in the Sustainability Roundtable with the Property Council. Experts such as engineers, social value specialists and biologists contribute to these papers. Feedback is collected and reviewed by the Technical Advisory Committee, which includes industry members from various sectors, academics, consultants, building developers and government representatives. Government agencies then use this feedback to create practical guides, which are published for free.

> *'It shows the industry how to do whatever is applicable. There's a practical guide for electrification, a practical guide for embodied carbon, and a pathway to net zero. That way, we get the research to inform our policy.' (GBCA interview)*

This reflects a tendency across the industry to encourage the adoption of a holistic life cycle sustainability approach. Most large companies that are GBCA members have internal ESG targets and must report on this performance to their boards. Gaining third-party certification is a useful way to determine whether those companies are in alignment with their ESG goals.

GECA is another third-party, non-profit organisation that will grant LCA ecolabels to companies. The majority of their listed products and services relate to the built environment. Other bodies like **Bureau Veritas** are approved as independent certifiers for large infrastructure construction projects. **CodeMark Certification Scheme** is another well-known, third-party building product certifier administered by the **Australian Building Codes Board (ABCB).**

It was noted that reform in global reporting has at least happened with two new **International Sustainability Standards Board (ISSB)** standards, the IFRS S1 and S2, which set a global baseline for companies to provide information about sustainability-related risks and opportunities. Corporations, therefore, have to become more transparent about stocks and supply flows to show their investors how they are behaving more resiliently. One of the key ways to demonstrate this is by demanding that suppliers demonstrate they are being proactive.

In addition, sustainable projects can win **awards and recognition** to attract new projects. For this reason, medium to larger tier 1 contractors invest in joining certification organisations and adopt sustainability frameworks, which empower their project managers and teams to collaborate on sustainable building projects from the onset through the completion of a site.

This means they would instruct their architects and engineers to deliberately cut down on unnecessary waste and embodied carbon in the production of supplies. These professionals are well-versed in using tools to select lower carbon materials, specify the installation of smart energy systems to realise lower operational costs and use BIM or digital twin programs to ensure all parts and components can be prefigured for assembly and disassembly in the future. These managers will determine whether prefabrication is the best option for a new structure or evaluate other elements that lead to lean construction.

Even though the industry may engage in certification and reporting practices, workshop participants voiced a concern that the current metrics are too general and should be improved by collecting and disseminating more specific information about products and services.

It was recommended that reporting account for the locations where materials are sourced, whether products are manufactured from raw or recycled ingredients and for companies to explain if manufacturing methods derive from renewable power or contain renewable resources. This information would clarify and avoid inconsistency across reporting practices to guide better procurement.

Policy and regulations

Through mandating change and incentivising sustainable practices at all levels, federal, state and local governments can accelerate the transition to a CE for the construction sector. Two ways to facilitate change are through policy and procurement.

Governments play a crucial role in advancing the CE within Australia's building industry by acting as both enablers and regulators. Through incentivising sustainable practices at all levels—federal, state and local—governments can ensure that their policies prioritise products that meet best practices for CE. This sets an example and stimulates market growth in the CE. As one participant noted, *'There is a lot of things policy and legislation can do to help kick start it [the circular economy].' (Adelaide workshop)*

Procurement plays a critical role in influencing and shaping CE principles and strategies and government intervention is essential to driving sustainable practices across the construction industry. This includes initiatives like preference procurement and setting regulatory frameworks for materials to meet circular benchmarks and to encourage sustainable design and practices. Therefore, as major procurers, governments have a significant influence on shaping industry standards and design practices through their procurement guidelines. As participants noted:

> *'Governments can be the **regulators for setting, I guess in some ways both standards** as we see through, for example, the national construction code or driving more ambition as I think we're starting to see certainly in New South Wales. And they're **doing that in collaboration with industry** because they're consulting with industry well on that.' (Sydney workshop)*

> *'In both of those is the regulatory framework, but also how **governments can act because they are large procurers of stuff that's supplied**. They can **influence it through their procurement guidelines**, and I think that's really important too. I think that's essential because **they need to be demonstrating what we want everyone to do.**' (Sydney workshop)*

For example, in July 2024, the Australian Government released an **ESP Policy** to apply *climate* (focusing on GHG emissions, energy efficiency and low embodied emission), *environmental* (focusing on water efficiency, renewable inputs, safe use and disposal of chemicals and waste minimisation) and *circularity* principles (focusing on keeping resources in use for longer and sustainable production and consumption). Specifically, the circularity principles underline the strategies focusing on less material use in buildings and fit-outs and they promote the use of durable, repairable, reusable, or recyclable goods, as well as leasing and renting services. Construction services at or above $7.5 million were one of the procurement categories that adopted a circular policy, which became effective on 1 July 2024. The federal government set forth metrics to make it easier for suppliers to know how to report during the transition in phase 1 (until the framework is finalised on 1 July 2025). A NSW Government representative noted:

> *'Environmentally Sustainable Procurement is guidance aimed at NSW government procurement professionals. It's a process-style document with templates. We give them the tools they need to guide them through the decision-making process of how to do more circular procurement and more environmentally sustainable.' (NSW Government interview)*

Public investment can act as a catalyst for private-sector engagement. By being the *'first loss investor' (Hobart workshop)*, the government can promote non-traditional methods and encourage private companies to leverage these initial investments. This strategic use of public funds can drive holistic improvements in the industry.

The **ReMade in Australia** program is another linked initiative—a certification trademark geared to reward manufacturers for producing goods with recycled content. By signalling to the industry that this incentive is forthcoming, participants believe it gives everyone in the supply value chain time to prepare. The government has an instrumental role in rolling out this program, not only mandating change but also being Australia's largest procurer of goods. This program can create a marketplace for recycled products. Because buying entails long contract periods, a member of the GBCA noted there would even be time to set up industrial hubs. Manufacturers could set up a concrete plant, for example, near a facility that would supply it with by-products for production.

Governments can foster a supporting environment by identifying **priority areas for investment** and ensuring regulations support sustainable innovation towards the CE. For instance, using a state-based or nation-based carbon budget for infrastructure projects can make a significant impact. This approach was highlighted by an example from the UK, where carbon budgets are used to assess the environmental impact of construction projects, prompting questions like,

> *'How much of the country's carbon budget is going to be consumed through that infrastructure project?' (Sydney workshop)*

While regulatory enablers are essential for cultural change, making it easier for companies to adopt CE practices, governments must streamline regulations to facilitate this transition, ensuring policies are clear and supportive of CE principles.

For example, incorporating CE principles into **tender management** processes can significantly impact construction and demolition projects, encouraging the use of recycled content and the recovery and reuse of materials and pushing companies towards the idea of deconstruction. As a NSW Government interviewee explained:

> *'You anticipate potential demand for recycled materials and help both agencies and eventually industry prepare for that.' (NSW Government interview)*

State level changes

At the State level, **planning reforms** are urgently needed around Australia, as attested by participants, particularly from ACT and WA. It would alleviate the national housing supply crisis by allowing 'missing middle' homes to spring up in existing urban or suburban areas. It takes the onus off building new homes during current high interest rates and construction costs. As argued by many architects and designers during the workshops and interviews, **adaptive reuse** (presented earlier as a CE design strategy) eliminates the need to demolish structures, prolongs the life of materials and gives significant value in avoiding unnecessary urban sprawl, among other benefits.

Introducing such planning reform will legalise divisions for dual occupancy, duplexes and townhouses on lots that were previously zoned for single houses. This step can be achieved by involving architects in delivering design through construction planning for redevelopment projects in established areas to facilitate housing density and diversity.

Following a persistent campaign, WA partially amended its residential design codes to reflect changing lifestyles and housing needs. These provisions encourage planting trees and gardens, more attractive streetscapes and better-designed houses with ventilation and natural light. However, WA's government decided not to force developers to retain trees and create more liveable areas in locales that comprise approximately 21% of all housing estates that proliferate on Perth's urban fringe. The government and its supporters argued it would make housing unaffordable compared with the current single-story standard. Many suburban communities are plagued by the urban heat effect in developments without a canopy. Nonetheless, as the Architecture representative explained, making this shift is challenging, as people are still dreaming about having single houses with picket fences. As they explained:

> *'In my practice, we try and make projects that have high impact. And we're making simpler buildings and new builds, but it's just that everyone is scared of the new or scared of what they don't know. It's the business-as-usual model. I keep saying to them, do you want to be Kodak, or do you want to be what the new thing is? The problem is that there's no need for them to move yet because there's no stick, and the carrot is still too appealing.' (Architect interview)*

NSW, on the other hand, has shifted to a new mandate along with other jurisdictions under a fast-track complying approval procedure. Their government engaged suitably qualified professionals to redevelop sites under guidance adopted by State Environmental Planning Policy 65. QLD also favours residential density that reflects the medium-density residential character of the area. NT is flexible with its codes which allow for blended low and mid-density dwelling types that respond to changing community needs and maintain the character and amenities of a zone. VIC is open to opportunities to place medium-density housing in metropolitan and major activity centres and identified urban renewal areas and locations supported by adequate public transport. SA similarly offers a range of needs and lifestyles located within easy reach of services and facilities that support city living. Tasmania is reviewing its standards to improve residential living with medium-density development.

Medium-density housing zones will increase cohousing and intergenerational living while alleviating cost-of-living pressures and the housing crisis. The rezoning also enables the conversion of commercial and residential spaces for multi-uses to expand the capabilities of existing assets. Implementation of longer-term measures can catapult business and society onto a trajectory to achieve more profound results.

There are other ways the government can leverage regions' strengths to generate sustainable and enduring economic growth towards well-planned, inclusive and resilient communities. Clever strategies for converting mass housing to more cost-effective, energy-efficient structures, adapting housing stock to accommodate multi-generational families. If that happens, people can move closer to urban or town centres, use cars less, cycle or walk to shops and work. Notably, the popular **Teilhaus design** (as presented earlier under circular design strategies) exemplifies the concerted efforts of government and industry to create an affordable and better housing future—one that is simplified and sustainable. Due to its success, iterations of this model have spawned nationwide.

Planners' uniformity among neighbouring states would be a way to provide greater options in waste reprocessing and overcome related obstacles.

Regarding C&D waste, state planning codes require reclassification. According to an SA consultant, their codes classify demolition waste as destined for landfill, so recyclers need the same processing approvals as landfill operators, which impedes options for reprocessing. Participants said that sometimes C&D waste cannot be transported across state lines if different rules prevent it from reaching regional waste management and resource recovery facilities.

State and territory programs

States and territories are also developing their own circular strategies. NT's **Department of Infrastructure, Planning and Logistics (DIPL)** has a climate change working group focused on initiatives to target emissions, which could lead to changing the design standards of all new government buildings. Further, the **Department of Environment, Parks and Water Security** is looking at new opportunities for C&D waste management.

NT is the only territory or state that has not implemented a waste levy. Waste levies are financial contributions that must be paid by licensed waste management companies for each tonne of waste sent to landfill. They are intended to encourage the diversion of waste from landfills to resource recovery. Although participants were generally averse to suggesting forms of punishment, preferring carrots to sticks to advance circularity, evidence reveals waste levies and fees are a remedy to curtail illegal disposal, which is urgent in NT, as testified by participants. For this reason, Tasmania released a waste levy in 2023 and the state is planning to fund programs and priorities for C&D waste.

A NSW Government representative provided a detailed overview of their efforts to introduce the CE. As an influencing and enabling team, they work directly with other government agencies to help increase the uptake of recycled materials and support the CE transition by developing tools and providing guidance in the decision-making process. They work on reporting requirements and aim to undergo a public consultation process to assess the feasibility of reporting on using recycled materials. Moreover, the CE team within the NSW Government holds an advisory role for the NSW Procurement team and officers and provides upskilling opportunities with respect to circular design. This includes assessing their operations and purchasing decisions and helping them identify circular alternatives. The agencies then have the flexibility to adapt and create strategies on their own. Thus, the government educates but does not mandate in this sense. The NSW participant also reflected on the 10R CE strategies and the 13 design strategies they created for the built environment:

> *'We've had a few preliminary conversations in agencies to understand that their 10R process. So like, are you rethinking to what extent do you need to build this new building? To what extent can you design more flexibly? To what extent can you reuse to deliver? So we've been trying to educate on that and then also, from the design perspective, we have our 13 design strategies and we're trying to promote the benefits to influence better design outcomes when it comes to planning buildings and assets.' (NSW Government interview)*

QLD is collaborating with Stanwell, a government-owned corporation that generates electricity, to gather input for smarter energy decision-making. GISA has been a forerunner of change, supporting the development of the CE through diverse partnerships to improve productivity, resource efficiency and resilience for decades. As a peak body representative noted:

> *'How we go about trying to write policy to have an influence on change is by showing leadership and demonstrating. It came by being first with bans on single-use plastic bags and supporting research that builds an evidence base, linking with that evidence to help the industry to be ready for all those implementations.' (Peak body representative)*

It is important to acknowledge that solutions must be determined for items that accrue and have no method for repurposing, especially solar panels. Due to its urgency, the federal government has listed solar panels for mandatory product stewardship. Instituting this high level of stewardship for more specific building materials or supplies with no readily apparent solutions and requiring responsible management is the best and quickest strategy. One government representative said **product stewardship** would at least be a vehicle for transparency to discover how products are being treated within supply chains to guide the implementation of circular initiatives.

While every state and territory has different guidelines and reporting requirements, they all seem to be actively involved in charting future pathways and participating in discussions with the government—as NSW Government participants explained. Similarly, a GBCA representative commented on the process of advising the government, explaining that for the advocacy side, the **Australian Sustainable Built Environment Council** represents various organisations in the built environment sector focused on sustainability. As the representative explained:

> *'The joint policy platform provided an overview of why things need to change, but also what can be done with practical policy suggestions for federal, state and local government. They were mostly focused on electrification or around energy efficiency. Every building counts is our report with the PCA. For example, in the residential space, we're asking for electric bounds on gas connections, for the phase out of gas for existing buildings and a timeline for that and some kind of mandatory disclosure of and at home energy rating that's uniform across Australia instead of having different state-based ones. And we want to have that as mandatory disclosure.' (GBCA interview)*

The government should carefully lift circular standards with open-market policies that enable competition, trade and investment.

Several government officials who work in natural resources and planning departments stressed that it is important not to be overly prescriptive in policymaking because sometimes unintended outcomes occur. However, participants believe certification and reporting schemes are insufficient to advance large-scale change without regulation. Governments at all levels have to provide impetus by setting a carbon pricing scheme and having states and territories collectively raise their landfill levies. With reference to earlier examples, under stricter conditions, companies will deem it more feasible to collect materials from old building sites for reuse, recycling or repurposing rather than to throw them away.

Legislation would, in turn, heighten the value of used parts and components to stimulate a circular marketplace. As one developer and an architect stated:

> *'Right now, it is easier not to store things when no one wants the materials you're demolishing, so incentives put in place by the government alongside investors and insurers would really accelerate the transition to circularity'. (Developer)*
>
> *'I think the only way this changes is at a legislative level.* ***Private industry's job is to show the way things can be done. But then it's the government's responsibility to turn that into scalable solutions*** *through broadly applicable policy. Because you can't just have these pockets of excellence and then 99% is still tanking it. Yes, we're all going to keep fighting the good fight, but it doesn't mean anything if everyone else is still dropping the ball.' (Architect interview)*

The 15-member **Circular Economy Ministerial Advisory Group**, established in February 2023, advises the Australian Government on the transition to a more circular economy and is actively working to foster well-crafted CE measures that will connect industry with government. During the completion of this scoping study, an interim report was issued in April 2024 to demonstrate the Advisory Group's early commitments. It contained a section on the construction sector and a final report is expected to be released in late 2024.

Meeting Paris Climate Change goals to target emissions influences future policymaking. NABERS, the national initiative that is managed by the NSW Government on behalf of all Australian governments, has a positive track record of advancing decarbonisation and electrification based on their recognised world-class rating system for 25 years. The Federal Assistant Minister for Climate Change announced recommendations to include more commercial building and ownership types.

In addition, one participant talked about the global initiative of **Building Breakthrough**, which was launched at COP28 to underline the critical role of buildings and the built environment in addressing climate change. Because the next wave of construction will take place in the Global South, there is an urgent need to guide this growth in a way that avoids locking in future emissions and uses materials wisely.

Part of the Building Breakthrough also includes assessing which countries have incorporated buildings and the built environment in their Nationally Determined Contributions under the Paris Agreement. This is vital because these contributions are part of countries' voluntary commitments to reduce emissions and respond to climate challenges. By evaluating National Adaptation Plans and Nationally Determined Contributions, the initiative aims to ensure that future buildings and construction are aligned with sustainable and systemic climate goals.

Under the Buildings Breakthrough, a list of 10 recommendations was put forward in early 2024, aiming to underline the critical role of **whole-life cycle policy thinking** in implementing Buildings Breakthrough initiatives to achieve near-zero emissions and resilient buildings. As a key outcome, the **Declaration de Chaillot** has been adopted by 70 countries, including Australia, to enable progress towards the transition of the building sector (Global Alliance for Buildings and Construction, 2024).

Two of the ten recommendations directly refer to the CE: *Recommendation 9: Material Circularity and Recommendation 10: Design for Circularity*. These recommendations focus on using sustainable building materials and components through improved data transparency and accessibility, supported by policies and market instruments. This involves implementing pre-demolition audits, material passports and standards to enable informed decision-making and facilitate material reuse. Standards, regulations and market instruments can enable secondary markets to balance supply and demand, with the government leading by example. In addition, designing for long service life, material efficiency and flexibility in new buildings can reduce resource use and emissions, supported by comprehensive data and LCAs (Global Alliance for Buildings and Construction, 2024).

There is now a Call for Submissions on the **Materials Hub Case Study Platform** in preparation for the COP29. The aim is to share impact case studies and best practices to advance the whole life cycle policy thinking and circularity in the built environment. The Materials Hub is hosted by the GlobalABC and managed in partnership with the One Planet Network and the Life Cycle Initiative.

Economics and investment

Tier 1 contractors are at the forefront of bringing sustainable, large-scale developments to Australia's major cities. Participants from the Sydney workshop explained that many of these companies are multinationals. Therefore, they rely on overseas pension funds to provide debt and equity finance, which propels them to set more ambitious goals. As such, they must be accountable because they move with global trends where sustainability is an expectation. These contractors report on the **Global Real Estate (GREs)** and try to position themselves as leaders in the Global Real Estate Environmental Sustainability Index, among other prominent indexes.

Several of Australia's largest investment funds were also identified as investigating responsible, ethical and impactful properties to include in their portfolios. **Cbus Super** evidences how a major superfund chooses to follow a responsible investment policy that takes a 'whole of fund' approach to their investment strategy, incorporating ESG risks and opportunities when making decisions. The sustainability strategy of their property division focuses on investing in better buildings, which is achieved by creating and managing world-leading buildings. They aim to deliver positive outcomes for the environment, communities, suppliers, customers, tenants and members by leveraging the capabilities of their onshore teams and working with offshore partners to create opportunities across private and public sectors.

Australian Ethical was named as another ethical superannuation, pension and managed fund provider. It seeks investments that support people, quality and sustainability. It holds a wide range of property investments in domestic and overseas markets, including publicly listed company shares (or equity), debt or cash products and investments in externally managed funds.

Australia's largest infrastructure fund, **IFM**, was also discussed in the workshops. They represent a global institutional investor and asset manager that pursues similar goals of delivering ESG outcomes that benefit the communities in which they operate and their investors. IFM has partnered with the **Clean Energy Finance Corporation (CEFC)** in a fund that set targets to cut the carbon footprint of their national infrastructure assets (Ausgrid, Melbourne Airport, Brisbane Airport, Port of Brisbane, NSW Ports, Northern Territory Airports) between 17% and 100% by 2030 besides disbursing finance for other Australian infrastructure projects. Nonetheless, it was acknowledged that smaller property developers, owners and renters miss out on sorely needed funding for better building projects. This is where a huge gap lies in the market. A participant from the not-for-profit ecolabel, GECA, stated that more incentives could benefit smaller manufacturers, such as paying exorbitant costs to create an EPD that shows the environmental performance or impacts of building products and materials over their lifetime.

Participants were asked if they knew of any public or private capital sources that might be accessed to fill funding gaps. **Power purchase agreements (PPA)** have been a successful way to develop greater clean energy capabilities and participants recommended implementing corporate PPAs that allow a business to purchase electricity directly from a renewable energy generator, e.g., solar or wind farms, to transition to a lower carbon footprint (see more information about ***RACE for 2030 CRC**** which investigates the transition to reliable, affordable and clean energy).

A participant from GBCA shared their insights regarding the value of research and, in particular, CRCs:

> *'It's just about trying to get that information across as quickly as possible. And we do that by trying to share our research with as many units as possible, through structured forums like the CRCs we're part of like Building 4.0 CRC and Race for 2030. They're focused on electrification and renewables. It's a really energy-focused CRC of which buildings are a group, particularly because there's massive opportunities for buildings in providing levers for flexible demand for the energy grid going forward.' (GBCA interview)*

For smaller businesses or homeowners, feed-in tariffs administered for homeowners to install solar power were

> ***RACE for 2030*** *– Accelerating the transition to Reliable, Affordable, Clean Energy for 2030*
>
> *RACE for 2023 leads collaborative research and innovation to reduce costs to business, enhance reliability, cut carbon emissions, improve energy affordability and develop Australian energy technology businesses*
>
> *The RACE for 2030 CRC had five research programs comprising 11 research themes: RACE for Business, for Homes, for Networks, for EVs, for Change.*

mentioned as a potential vehicle to spur more low-carbon buildings. In addition, workshop participants recommended that banks offer bridging finance to consumers to purchase homes with lower footprints.

Money collected from waste levies to fund circular business grants was also raised as an option to underwrite better building initiatives. An attendee from the Tasmanian Government thought public investment funds at a first loss might be made available to start new initiatives to drive improvements in construction.

Although forms of niche funding are more limited, participants claimed venture capitalists might be willing to invest in sustainable construction projects with viable, long-term prospects. Pitching the merit of operating CE buildings more economically over the long term would help to overcome investor reluctance if a construction project appears to have promising future returns on a balance sheet. A representative from Australian building developer, Stockland, asserted that new residential buyers seek to invest in energy-efficient homes. Fellow workshop participants reinforced that higher energy efficiency drives both average rated lease expiry and capital value of commercial buildings. There needs to be better motivation to invest in CE products, recognising the long-term benefits and sustainability:

> *'There needs to be some way of recognizing that that is a single use product, whether it's taxed, whether it's, you know, there's additional carbon budget costs associated with it.' (XFrame interview)*

Insurance

Insurance is necessary for building and owner protection, but participants contend coverage is not always guaranteed. When a building meets product-specific ecolabel criteria based on LCA and the materials demonstrate compliance with product function, insurance companies should be willing to provide coverage, but insurance may be denied.

Further, there may be occasions when a building is constructed and deemed safe by a surveyor or the fire authorities, but insurers will refuse coverage, or premiums are beyond the company or consumer budgets. For these reasons, a Melbourne architect advises that it is best to check with insurers early in the building process to ensure they will grant coverage, especially under circumstances when a design or the materials might be unconventional, or a site is in a high-risk zone prone to bushfires, cyclones or flooding (however, considering the impact of high-risk zones is applicable whether the building implements CE principles or not). Otherwise, it can become too costly to rectify the problem.

Today, every commercial and residential insurer offers comprehensive online guides for building owners and occupiers. It is essential to read the rules for applicable risks and heed tips for property insurance to ensure companies and consumers can obtain adequate commercial or household insurance at the lowest possible rates.

Risk management

In light of climate change and pressures for companies to work towards ESG targets, participants said organisations have begun to issue their own incentives for risk management. A staff member of **Aurecon** was aware of public work contracts that include clauses to reward employees with bonuses for achieving carbon reductions—for example, current terms by a water utility company target reductions in embodied carbon of capital items. In the future, companies will likely introduce incentives for employees who can lower operational carbon.

Although technology cannot prevent natural disasters, accelerated use of technology in smart building devices can make communities safer, especially if power is connected to renewable energy providers. Moreover, technology can aid the insurance sector in assessing risk profiles more accurately and help with preventative measures or emergency management. **Digital twins**, as discussed in the ***Technology section***, can be used for scenario analysis and risk assessment.

Similarly, insurers must assess the risk profile of used building products through recertification. Testing their provenance through **blockchains** and distributed ledgers can facilitate tracking materials to assure their quality and structural stability. Otherwise, the insurers will likely refuse to back circular options for reuse, recycling or repurposing under normal conditions.

There was consensus among workshop participants that if you do not have a system that lends assurance of the outcome of salvaging materials, insurers will only opt to give coverage for buildings with new materials. The government can play its part in releasing regulations to pave the way for repurposing building materials, leading to recertification and open markets for the circularity of used building parts and components.

How to get there?

This section proposes some practical guides and tools to support the transition toward CE practices.

Circular Action Guide

The **Exponential Roadmap Initiative**, in partnership with **Cradlenet**, has published a **Circular Action Guide** to help companies cut emissions and natural impacts from material use in their value chain. Aiming to achieve zero impact, they summarised seven key actions (Falk & Roupé, 2023). Regarding their guide, we presented key strategies, principles and initiatives that are applicable to Australia's construction and built environment. A key aspect we wish to highlight is the reiteration (Figure 47), highlighting that the CE transition is an ongoing, dynamic process that needs continuous reassessment.

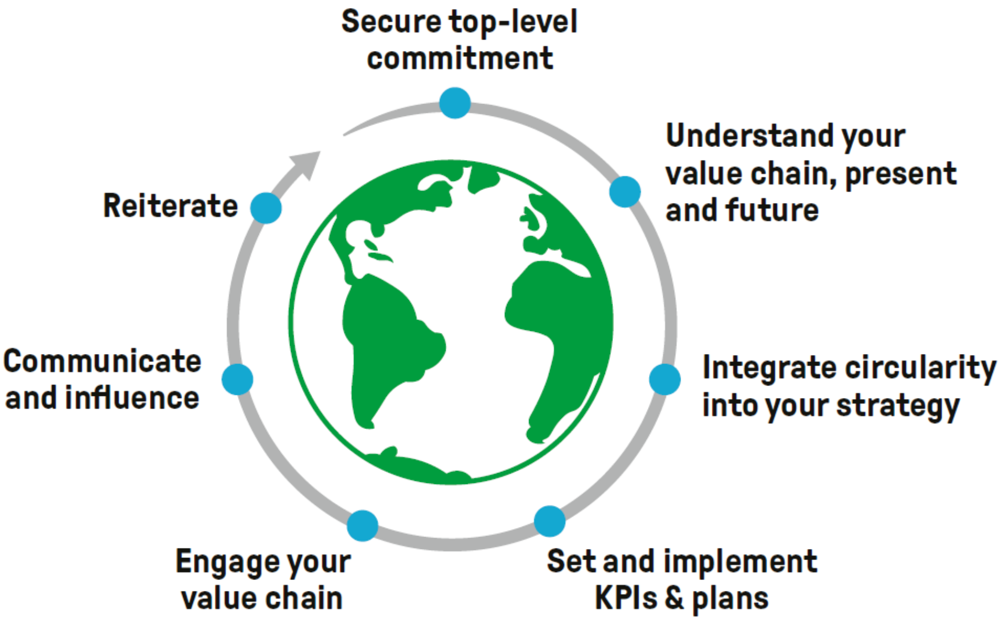


Figure 47. Seven key actions to drive a circular transformation
Source: Falk and Roupé (2023)
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Circular Transition Indicators

In the transition from linear to circular models, companies need to equip themselves with new ways of measuring progress in circularity. Built for business by business, the **Circular Transition Indicators (CTI)** is a framework that brings together critical metrics that are adaptable to businesses. Measuring impact remains a key barrier in the CE transition and, therefore, the CTI provides a solution. In their updated Version 4 of the framework, Falk and Roupé (2023) included GHG impact to give a holistic understanding of the carbon footprint of the company's products and materials. Based upon the work of 30 WBCDS members, the CTI allows companies to answer the following:

- *How circular is my company?*
- *How do we set targets for improvement?*
- *How do we monitor improvements resulting from our circular initiatives?*

In partnership with Circular IQ, the CTI online tool is available and accessible at https://ctitool.com/. The CTI tools build upon four key indicators that can be categorised as:

- ***Close the loop*** (% material, water and renewable circularity)
- ***Optimise the loop*** (% critical material, % recovery type, actual lifetime, onsite water circulation)
- ***Value the loop*** (circular material productivity, CTI revenue)
- ***Impact of the loop*** (GHG impact, nature impact)

The CTI framework outlines seven process steps that cover the assessment cycle.

Circular Buildings Toolkit

The **Circular Buildings Toolkit (CBT)**, developed by **Arup** in collaboration with the **Ellen MacArthur Foundation,** is a comprehensive resource designed to support designers, construction clients and asset owners in adopting CE principles in the built environment. This toolkit recognises that buildings are responsible for 37% of global GHG emissions and much of the construction material value is lost due to traditional and linear 'take, make, dispose' practices (Arup, n.d.).

The CBT offers actionable strategies for overcoming this wasteful model. It focuses on building with the right materials, cutting waste across the supply chain and planning for long-term value. By promoting low-carbon, renewable materials and providing a library of successful case studies, the toolkit equips industry professionals with the knowledge and confidence to design buildings for longer-term use, reduce emissions and meet net-zero goals (Arup, n.d.).

One of the key aspects of the toolkit is showcasing completed projects, which prove the practicality of CE in buildings. The **Full Library of the Toolkit** provides more information and examples. The case studies are categorised according to the different elements implemented and the countries in which they are implemented. For example, evidence is presented for additive manufactured structures, modular systems and bio-based façade systems. In particular, there are seven Australian case studies on this site (Arup, n.d.).

The roadmap of CBT proposes seven steps:

1. *Learn about the Circular Economy:* Benefits explained in relation to risk mitigation, reducing waste and the use of raw materials, long-term value capture, increased resilience and new economic opportunities
2. *Get familiar with the framework:* The toolkit proposes 11 strategies along four key segments that focus on: build nothing, build for long-term value, build efficiently and build with the right resources
3. *Learn about strategies:* This is in reference to the 11 strategies proposed under the framework
4. *Explore practical case studies:* Use the Full Library of the Toolkit presented before
5. *Organise a circular design workshop:* The toolkit proposes ways to organise circular design workshops with experts, most importantly, they offer a Workshop Guideline with activities
6. *Track your project:* Arup allows companies to create a portal and upload their project for tracking purposes

7. *Implement strategies:* Once familiar with the circular strategies, next step is to implement them

Renovation and climate-ready homes

To support Australia's Net Zero Plan, the **Climateworks Centre** has released the ***Climate-ready Homes Report***, outlining strategies to enhance energy efficiency in existing buildings and reduce emissions (Armstrong et al., 2024). A key focus is on improving the thermal shell of homes—the walls, floors and roofs—so that they retain warmth in winter and stay cool in summer, enhancing overall energy performance. The extent of thermal shell upgrades required varies depending on the specific climate in which a home is located. Given Australia's diverse climate, NatHERS has divided the country into 69 distinct climate zones to guide these upgrades.

In general, homes located in states and territories with hot, dry summers and very cold winters benefit most from thermal shell and space conditioning upgrades. These improvements are crucial for maintaining warmth during winter, leading to more significant energy savings and comfort. Meanwhile, homes in hot, humid climates with distinct dry and wet seasons see greater energy reductions by upgrading hot water systems to electric and replacing gas cooktops with induction, which is more energy-efficient and reduces emissions.

Climateworks also provides and compares three different upgrade levels across the states, namely, quick-fix, modest and climate-ready, with cost estimations and the resulting emissions reductions and cost efficiencies.

Building Circularity 4.0: First Steps to Adoption

The Building CRC developed a new tool, together with the Circular Economy Ministerial Advisory Group, called the **Building Circularity 4.0: First Steps to Adoption framework**. The framework provides an overarching understanding of the key players in the building supply chain and suggests actions each player can take to introduce CE principles. The framework addresses and divides the stakeholders according to construction, supply chain, consultants, finance and property, representative bodies, government and policy and owners and end users.

One key suggestion for the Federal Government is to *'Create a roadmap to guide all actors within the building life cycle to implement circularity.'* Therefore, this is the premise of this study and in the following section, we present our roadmap to a CE in the building industry.

BUILDING THE FUTURE ROADMAP

Recommendations of this scoping study reveal how Australia can advance in its CE transition by taking advantage of readily available and foreseeable solutions in designing smaller footprint sites, retrofitting over new builds whenever possible and taking advantage of planning law reforms in jurisdictions for adaptive reuse. The recommendations are intertwined with introducing skills and training for CE through education provided by vocational and tertiary institutes and professional bodies while labour shortages prevail.

The scoping study underlines that key research, policy and capability elements are in place, but more need to emerge. Australia requires **continuous improvements in tools and strategies** for change. The principles of the CE identified during the current scoping study have been translated into a roadmap to enact actions to implement more circular buildings and infrastructure that reduce waste, water, energy, carbon and pollution for a healthier country.

Transitioning to a CE requires time. It takes time to develop hubs, circular supply chains and regulatory conditions that are conducive to CE. These conditions also need to create consumer confidence and structural stability to offset risks and bring competitive costs, making sustainable and circular construction accepted and sought after.

Having developers and owners commit to completing more circular projects will help to create market momentum with government incentives.

We can make a significant difference in 'Building the Future through the Circular Economy', which advances SDG 11, sustainable cities and communities; SDG 12, responsible consumption and production; SDG 13, climate action; and SDG 17 partnerships for the goals, among others. While developments incorporating circular applications are unfolding, they arise predominantly as standalone or smaller developments rather than occurring holistically across our nation. The findings also indicate that momentum is building and will continue to be driven by need and consumer demand, with more and more people embracing circular practices.

The call to action has been around for a while.

While the tasks and trajectory to reach meaningful change are formidable, awareness of what we face as a society is acute. It is incumbent for everyone to shoulder responsibility in this 'critical decade' to navigate a better building future through efforts of concerted partnerships. What follows are recommendations to embrace pathways to accelerate circular change from descriptions and links to available and foreseeable opportunities in the near term.

The next steps of delivery may be tied to future building projects such as the Brisbane 2032 Olympics and Paralympics and forthcoming infrastructure for better roads and rail networks to link our nation and meet the needs of businesses, governments and communities. However, retrofitting of existing buildings also needs to be addressed.

Government, industry and academia should harmonise joint efforts to create synergies to accelerate circular construction using early intervention to ensure the best chance of circular success. Our research reflects that Australia has many sustainable buildings and infrastructure, which have the potential to converge practices towards greater circularity. This scoping study is intended to bridge the efforts of all actors to bring meaningful solutions for change.

The CE roadmap, outlined in Figure 48 and Figure 49, presents a comprehensive framework across three key pillars: **Circular Economy in Construction**, **Circular Supply and Value Chains** and **Circular Economy Enablers**. This roadmap is designed to guide businesses and stakeholders in adopting circular principles across various levels of operation, from individual companies to broader ecosystems and industry-wide collaboration. In the detailed description in Table 14, specific actions and tools are proposed along the key sub-themes.

The first pillar, **Circular Economy in Construction**, focuses on strategies that can be implemented at the micro and business level, emphasising the importance of (re)designing for CE and ensuring that construction processes are sustainable from the outset. This includes designing for deconstruction, allowing materials and assemblies to be easily reused and incorporating renewable energy sources in the construction process itself. Businesses are also encouraged to focus on alternative materials that minimise waste and avoid contamination. In addition, LCAs play a crucial role in evaluating the environmental impact, while strategies such as renovation, retrofitting and better waste management ensure resource efficiency throughout a building's life cycle.

The second pillar, **Circular Supply and Value Chains** operates at the meso-level and calls for businesses to integrate circular principles into their entire value chain. This involves embedding CE into the core of the business strategy and participating in material marketplaces that enable the exchange of recycled or upcycled materials. The development of local circular hubs, organising and attending industry events and fostering a whole ecosystem perspective are essential in promoting circular practices across supply chains. Businesses are also encouraged to form network governance consortiums, ensuring collaboration and oversight in the implementation of circular strategies.

The third pillar, **Circular Economy Enablers**, addresses the macro-level, identifying key factors that enable or hinder the adoption of circular practices. These enablers include technology, such as prediction and documentation tools, database solutions for tracking circularity metrics and improved waste management systems. Education is also a key part and training the workforce and engaging in ongoing capability building is vital to ensure that businesses are equipped to implement circular strategies effectively. Certification and reporting standards, social and biodiversity inclusion and ensuring compliance with CE goals are also critical enablers. Moreover, economic incentives, such as financial rewards for sustainable practices, climate targets and open-market policies, all contribute to promoting CE, while financial punishments and stricter regulations discourage linear practices.

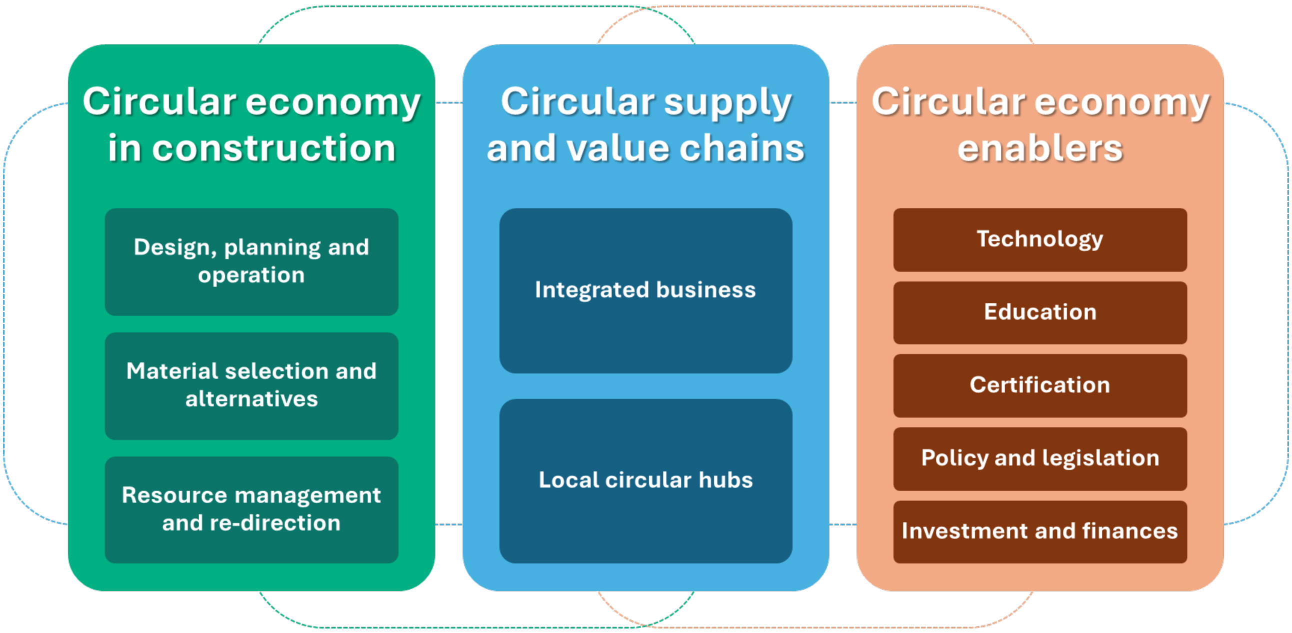
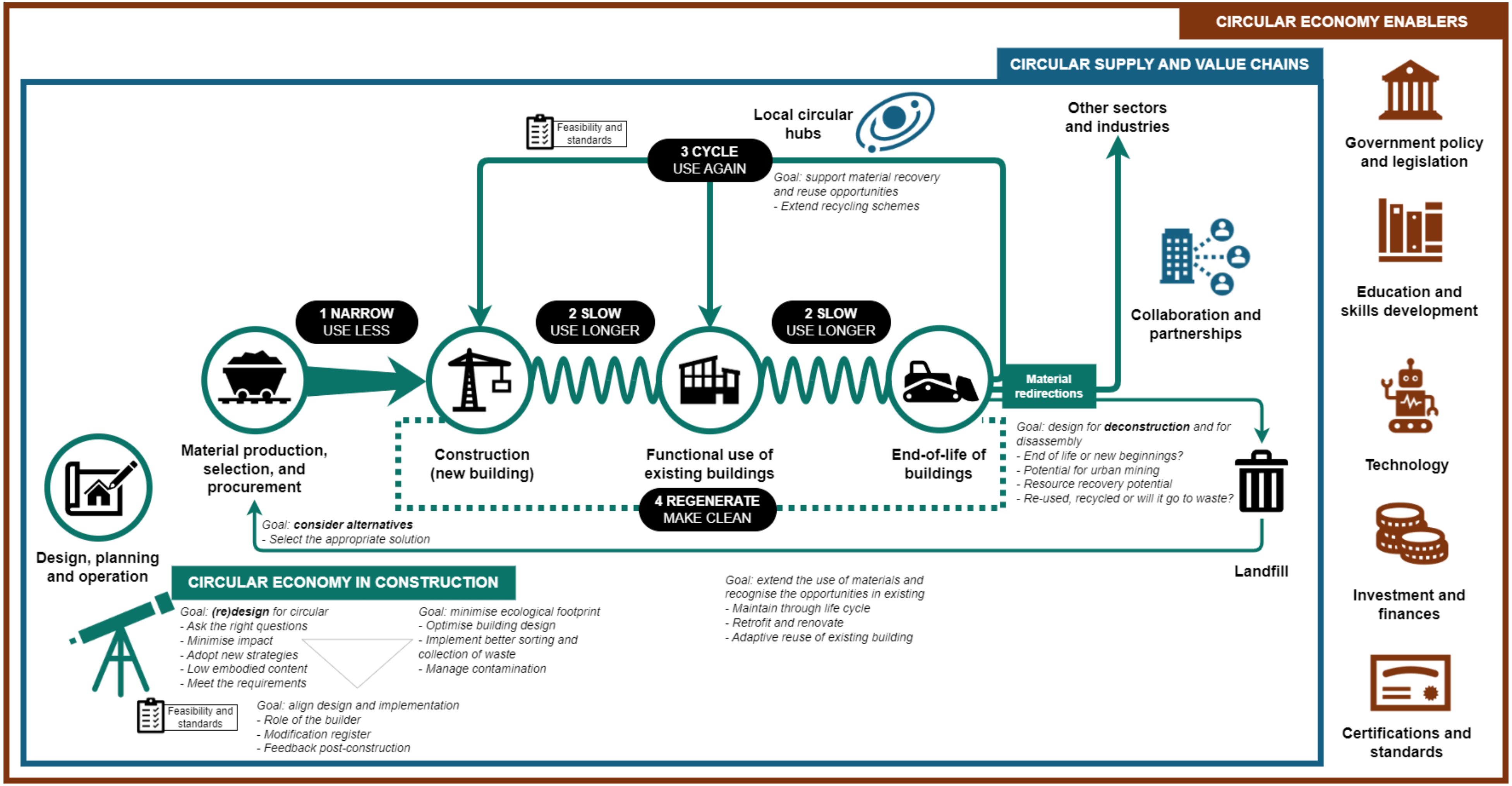


Figure 48. Key pillars of the circular economy roadmap in the construction industry
Source: Own elaboration



Whole-system and ecosystem perspective of circular construction

Figure 49. Overview of circular economy roadmap in the construction industry
Source: Own elaboration

Table 14. The circular economy roadmap in the construction industry
Source: Own elaboration

Circular economy in construction

SUB-THEME	ACTION	TOOL EXAMPLES
DESIGN, PLANNING AND OPERATION: Design projects and products with CE principles, focusing on longevity, repairability and design-out overconsumption.		
(Re)Design for CE	Ask the right questions and identify the need: What do we want? Why do we need it? Rethink, refuse or eliminate (virgin) resources and design out overconsumption Minimise the environmental footprint and evaluate the size of the housing Prioritise reuse and refurbishment over building new Strategies: Passive design (local climate), prefabrication, modularity, Teilhaus, conservation, permaculture, vernacular architecture, adaptability …	10R hierarchy and strategy of circularity Ellen MacArthur Foundation Circular Economy Butterfly Diagram 13 Circular Design Principles of NSW Government New ISO standards for circular economy Design for Disassembly by Coreo and Built Your Home guide Rewiring Australia
Design for deconstruction	Facilitate future deconstruction and disassembly Facilitate material recovery Move from demolition to deconstruction Consider product as a service and sharing facilities: explore business models to lease and share products	
Renewable energy and electricity	Decarbonise (fossil) energy demands in buildings, use renewable energy where possible Lower embodied carbon, operational energy and GHG emissions Lower energy demand in buildings by improved insulation of new buildings and retrofitting of existing buildings Support installing PV on rooftops, heat pumps, batteries for storage of energy, …	
MATERIAL SELECTION AND ALTERNATIVES: Encourage the integration of circular materials and exploit the potential to reclaim and reuse traditional materials and alternative materials and assemblies.		
Circular content	Integrate reused, recovered, recycled material Reduce virgin material use, 250 Mt virgin vs 25 Mt recovered materials—the market is not ready to meet demand and replace with recycled and reused only Shift from reliance on virgin material to rethink design	Environmental Product Declarations (EPD) *Example: BlueScope Steel* Extend the Construction Plastics Recycling Scheme in other states Extend battery recycling facilities (such as for Li-Ion batteries and
Alternative materials	What alternatives are there to meet these needs? Materials with a low environmental impact Lower embodied and operational carbon in concrete, steel	

	Bio-based and environmentally friendly Seek local supplies	product stewardship to avoid stockpiling) Urban mining potential (for materials like aluminium and glass, but also windows, doors and appliances)
Material contamination	Address asbestos, PFAS and battery contamination Ensure safe handling and processing of waste Separate collection of batteries at construction sites More collection/drop-off points for batteries	
RESOURCE MANAGEMENT AND RE-DIRECTION: Focus on existing buildings to extend their life cycle and reduce the need for new construction and resources.		
Life cycle assessment	Understand and improve the circularity of your products and operations Maintain products and material though their life cycle Monitor reuse opportunities: keep track of material flows, regulations and continuously assess market demand Caution: LCAs and EPDs are costly Develop Australian specific data sets for LCA	Environmental Product Declarations (EPD) *Example: BlueScope Steel* Life Cycle Assessment One Click LCA® software tool Revit Climate-ready homes guideline by Climateworks
Renovation and retrofitting	Existing buildings: ensure proper ventilation, lighting, shade, insulation (continuous process) Adaptive reuse of unoccupied structures and rezoning to meet housing demand Preserve what exists and conserve energy and other natural resources	
Better resource management and resource re-direction	Promote source-separation at construction sites and ensure effective segregation of waste streams in collection bins Engage waste companies and recycling experts in the design phase to improve resource recovery and recycling processes Educate workers at construction sites about better waste management How can the resource be re-directed into the economy?	

Circular supply and value chains

INTEGRATED CIRCULAR BUSINESS: Circular economy should be part of your strategy and business model to ensure commitment and efficient outcomes.		
SUB-THEME	ACTION	TOOL EXAMPLES
Embed CE into *your* strategy	Select the most appropriate solution to the needs/requirements Commit to meaningful targets for the CE: go beyond recycling of materials, but focus on environmental impacts, decarbonisation, water use, regeneration of nature, lowering the environmental footprint of buildings Align design and implementation (construction)	Planetary boundaries metrics or framework Circular Transition Indicator (CTI) Circular Action Guide

	Implement a *modification register* to track on-site changes (ensuring that any deviations from the original design are documented and communicated, such as post-construction feedback to designers)	Circular Buildings Toolkit by Arup Events by MECLA Events by Planet Ark Circular Economy Hub
Material marketplace	Promote procurement of circular materials (Government, business and academia coordinating a strategic plan) Establish take-back systems and reverse infrastructure and promote the 'redirection' of products and materials Carefully assess the resource recovery potential, as well as storage and responsibility implications	
Organise and attend events	Participate in networking events: These events foster essential conversations covering stages from early contractual agreements to design considerations and adaptive reuse, promoting reuse and preventing waste. Work together with different actors across the value and supply chain	
LOCAL CIRCULAR HUBS: Develop local supply chains and circular hubs for circulating materials, including reprocessing parts and components.		
Develop local hubs	Promote cradle-to-cradle accountability Exchange by-products through industrial hubs rather than stockpiling and connect with other sectors and industries Promote industrial symbiosis and benefit from these synergies Establish reuse and recycling hubs (especially in regional and remote areas like Tasmania or the Northern Territory)	
Whole ecosystem perspective	Assess your system and understand the key players Place CE within the wider sustainability network Establish collaboration along your value and supply chain and promote feedback of information and materials Develop a comprehensive understanding of systemic connections within your supply chain and environment—*Who is included? Who is impacted?* Use Integrated Project Delivery (IPD) and distributed manufacturing approaches to enhance collaboration and efficiency	Building Circularity 4.0: First Steps to Adoption framework Events by MECLA Events by Planet Ark Circular Economy Hub Network Governance Examples
Network governance consortium	Establish network governance consortium along your value chain to drive circular economy Develop tailored approaches: Address geographical disparities and uniqueness, ensuring supply chain efficiency and sustainability	

Circular economy enablers

<table>
<tr><td colspan="3">TECHNOLOGY: Discover and consider both simple and advanced technological solutions to enable CE.</td></tr>
<tr><th>SUB-THEME</th><th>ACTION</th><th>TOOL EXAMPLES</th></tr>
<tr><td>Prediction and documentation</td><td>BIM or digital twins can be used to predict events, facilitate as-built documentation, support maintenance and keep construction records up to date

Ensure any alterations from original plans are updated in BIM systems to facilitate future deconstruction—however, be aware of feasibility of tracking processes in BIM

Forecast and streamline processes</td><td rowspan="3">Revit

Rhino

Excel spreadsheet

SharePoint

Integrated Management Systems (IMS)</td></tr>
<tr><td>Database solutions</td><td>Manage, share and track data using smart software systems with a library to understand material and business resources flow, collaborating with partners to enhance these databases.

Assess and balance the feasibility vs benefits of tracking, prioritise selective tracking ensuring that the tracking process adds value without being overly complex or costly.

Use Excel spreadsheet or SharePoint site to track materials or more evolved technologies like blockchain or material passports (keep up to date with these advances)</td></tr>
<tr><td>Waste management</td><td>Divert waste from landfills (already at 80% for C&D waste)

AI for robotic sorting and separation of waste (HSE)

Forecast and streamline processes</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td colspan="3">EDUCATION: Develop and deliver training programs, share best practices and engage with institutions to equip the workforce with skills for circular buildings.</td></tr>
<tr><td>Train the workforce</td><td>Develop training programs to equip the workforce with the skills necessary for circular practices

Investigate and teach alternative construction methods that support CE and resource efficiency

Involve building certifiers (certify reclaimed material) and change the insurance system to allow material reuse</td><td rowspan="2">22667VIC Course in Circular Economy Practices

Circular Economy Hub@RMIT

‘Circular Economy Fundamentals’ by ACE Hub

Case studies by ACE Hub

Case studies by the Ellen MacArthur Foundation

New ISO standards for circularity

Your Home guide</td></tr>
<tr><td>Ongoing capability building</td><td>Identify and use educational and learning outlets that best support your needs, such as TAFE, universities, professional bodies, vocational and tertiary institutions

Local associations and symposiums (greater outreach)

Keep up to date with the circular economy field and how to measure achievements with examples of Australia in a boost to people, profit and planet—jobs, affordable housing, higher productivity, tempered and tailored development and better industry standards</td></tr>
</table>

Share best practices	Distribute case studies and best practices to illustrate successful CE applications and initiatives. Leverage others' best practices and learn from demos Use social media to promote educational content on better and circular building practices Organise public awareness campaigns, e.g., to not dispose of (Lithium-ion) batteries in landfill or recycling bins	
CERTIFICATIONS: Raise reporting, licensing and certification standards to promote CE and incorporate social, biodiversity and well-being.		
Different certifications and reporting	Reporting and disclosure for driving change Involve building certifiers for higher standards (i.e., 7-star) Implement licensing requirements for companies engaged in demolition work to ensure safety and professionalism in handling hazardous tasks.	Green Star training course GBCA Green Star Performance v2 (launched in July 2024) GECA National Building Code 7-star energy under NatHERS GBCA Nature Roadmap LEED NGER Navigating the circular economy reporting landscape by the Ellen MacArthur Foundation
Promote CE standards	Licensing for deconstruction work Real estate and property market Safeguard mechanisms through potential third-party assessment to verify circular content Streamline reporting: Focus on limiting the number of reports related to CE and use the required tool to ensure they contribute effectively to achieving CE goals	
Social and biodiversity inclusion	Extension of programs to include social sustainability and biodiversity Health, fitness and well-being components Transparency	
POLICY AND LEGISLATION: Ensure compliance with evolving regulations, promote uniform standards, collaborative procurement, and open-market policies.		
Ensure compliance	Stay informed about new regulations and government regulations (e.g., NCC, state planning codes, local legislation, 7-star energy rating) Leverage new opportunities (e.g., products and technologies, medium and higher density houses) Promote uniformity among neighbouring states and across nation to support waste reprocessing and streamline cross-border operations Federal, state and local governments need to work more hand in hand to achieve CE in the building sector Carefully consider waste levies or penalties for materials sent to landfills to encourage better sorting and diversion practices. Caution to unintended waste dumping	Circular Economy Advisory Group Environmentally Sustainable Procurement Policy ReMade in Australia program National Waste Policy National Building Code 7-star energy under NatHERS Top tips for 7-star

Collaborative procurement	Consider embedded carbon early on and how to reduce carbon in project delivery Government procurement and policy mandates – 1 July commitment to construction services valued at AUD 7.5 M Government to trial various methods of introducing circularity in projects Consider all environmental impact categories Providing this assurance should also affect client decision-making alongside creating motivation through rebates or schemes that will foster the adoption of CE	
Open-market policies	Advocate for stronger regulatory requirements and government policies that carefully raise circular standards while enabling competition, trade and investment Government to support the adoption of new business model to bring business to 7-star levels Update the NCC to allow for recycled products, mandate better insulation, resource-efficient installations (rainwater tanks, solar panels, heat pumps), mandate minimum green space around buildings (to allow rainwater uptake by soil) and encourage planting of native plants Stimulate competition and develop a circular marketplace Dynamic adaptation	
INVESTMENT AND RISK MANAGEMENT: Leverage green loans, rebates and grant schemes, while utilising landfill levies and investments in renewable energy.		
Economic incentives	Make circular options more attractive and competitive and encourage the use of LCAs, EPDs and circular models Clean Energy Finance Corporation (CEFC) Green loans, rebates, grant schemes, premiums	Green Bond Framework (7 billion green loan) Circular Plastic Australia under the CEFC investment City of Sydney Green Building Grants SMEs funding for LCAs and EPDs
Financial punishments	Landfill levies to reduce waste sent to landfill Controversial impact on asbestos	
Climate targets	Investment: green hydrogen and ammonia, green steel, renewable energy Decarbonisation and net zero Insurance and risk management and the price of not implement circular strategies Climate risk adaptation	

Note: The links and recommendations in this roadmap are not exhaustive. Due to the sheer size of Australia and the state of flux within the industry, new initiatives are frequently emerging. If the government of your state or local jurisdiction is not mentioned under one of the categories, we recommend you send an email to your branch of government or consult the building code boards to ask them about circular building practices. If they do not have an initiative in place to lower energy and waste, conserve resources to promote biodiversity and healthier surroundings, or incorporate sustainable building practices, demand change. There are many advocacy groups that may already be campaigning for action on the same cause, such as MECLA and Planet Ark Australian Circular Economy Hub. They can guide you further.

FUTURE EXECUTION AND IMPLEMENTATION

Transition to the CE will require ongoing and more profound initiatives as climate change and other forces prevail. The outcomes will be contingent upon mobilising a groundswell of support and action from all actors to implement these constructive measures, leading to the development of a critical mass that embeds CE firmly within the Australian construction industry. Government, industry and academia at the top must lead best practices with citizen participation at the bottom.

This scoping study contributes to a better understanding of CE practices in the built industry in Australia, supported by best practice examples. It provides a comprehensive overview of key themes and recommendations, summarised in the roadmap. In addition, this study highlights key gaps and future research areas that require further investigation and more detailed observation to support the CE transition. Our suggestions and future research areas are presented below. In this section, we propose the following future phases of research to implement the circular strategic action plan for building the future and enacting long-term change.

Circular economy in construction

- **Design and planning**
  - **Permaculture integration**: There is a lack of applied examples integrating permaculture principles into building designs despite their potential benefits.
  - **Green hydrogen technology**: Hydrogen presents a promising option as fuel for heavy vehicles. Waste companies could explore producing hydrogen from water, landfill gas, or organic waste.
    - Future Fuels CRC: Investigate initiatives like the Future Fuels CRC for advancements in hydrogen technology.
- **Materials**
  - **Develop assemblies:** investigate developing "assemblies" such as prefabricated building systems that have embodied energy and value through their initial fabrication but subsequently do not need to be broken down to be re-used in another structure.
  - **Timber supply and compliance**: Address the gap in tracking timber quantity and **sourcing, focusing on ensuring compliance with bushfire regulations in Australia.**
  - **E-waste**: establish a CRC for a Circular Economy of Electrical Devices.
  - **Alternative materials from other waste streams**
    - Investigate waste from other sectors that could be used for the building sector.
  - **Nature-inspired, carbon neutralised mechanisms**
    - Architects and engineers seek ideas from nature to instil regenerative approaches in design that will reduce carbon while promoting biodiversity and preserving ecosystems. Biophilic techniques are utilised to accomplish healthy, sustainable and resilient environments and can be developed to solve a host of construction applications. Further, waste materials can be used as resources for bioremediation that will not contribute to the depletion

of natural resources. Embedding biotechnology therefore has merit and offers pathways for circular construction.

- **Disaster and climate resilient materials**
  - Research is critically needed through civil engineering to continue arriving at solutions for disaster and climate resilience, specifically the ability of sites and systems to withstand and adapt to climate resilience or recover from natural disasters. Thus, it is imperative to not only develop strategies for protection, but to continue to develop better materials for prevention, to combat frequent and severe calamities ahead. These are principles for engineers to follow when creating disaster and climate resilient materials.
- **Adaptive engineered materials**
  - An exploration of the evolution of sustainable building materials should be conducted to assess which ones are emerging or commercially available, where they are located in close proximity to Australia and which ones have the best chance of coming to market here. A wide array of innovative and environmentally friendly materials should be scrutinised, ranging from synthetic to bio-based alternatives that include nanotechnologies to reshape materials and methods of construction.

- **Resource management**
  - **Battery recycling capacity**: Australia currently lacks sufficient capacity for recycling batteries (especially lithium-ion batteries), requiring improved infrastructure and processes.
  - **Material knowledge and standards**
    - Stock and flow information: Improve knowledge about the stocks and flows of materials, including volumes and sources, to support effective circular planning and material reuse.
    - Standardization issues: Develop best practices and standards for material reuse and address the financial burden of re-certification processes.
  - **Circular and redirected material availability**
    - Assess material availability: Evaluate the availability of recycled materials to meet industry needs and balance industry needs with circular economy practices.
    - Annually, 25 Mt of construction and demolition (C&D) waste are produced, with an 80% recycling rate. However, the building sector's demand exceeds this supply and only a small percentage of virgin materials can be replaced by recycled materials. Caution is needed in procurement requirements for high recycled content, as the market may not meet this demand.
    - Design-out overconsumption of virgin materials.
    - Address transport and legal challenges: Tackle varying laws across states related to waste transport and reuse and explore methods to streamline these processes.
  - **Resource recovery auditors**: Engaging resource recovery auditors to evaluate the products and materials removed from sites can support the shift from demolition to deconstruction, identifying opportunities for reuse or resale.
    - C&D waste has already reached the National Waste Policy Target 3, i.e., 80% average resource recovery rate. Invest in research to increase the resource recovery rate of other waste streams associated with the building and construction sector.
  - **Australian specific data sets for LCA**
    - Develop LCA data sets for Australia to improve LCA and reduce the reliance on global data sets.
  - **Life cycle sustainability assessment (LCSA) metrics**
    - Investigate the relevant parameters and impact categories. While environmental impact categories are well-established, the social dimensions

remain unclear in the building sector. Developing a consensus on these social impact metrics is crucial.

Circular supply and value chains

- **Support local opportunities**
  - **Circular hubs**: While the concept of circular hubs is not new, it is much more established in other parts of the world. The industry needs to focus on developing these hubs locally.
    - Researchers should also determine the best locations to set up or redesign market hubs for collection of materials to be recovered and reprocessed, having businesses collaborate with government to secure approval for the roll-out of industrial hubs around Australia.
  - **Market development**: Develop new markets and improve knowledge about material locations and how they can be recirculated into the system.
  - Implementation of **network governance or a consortium**
    - Investigate the Dutch steel or concrete network governance consortium and evaluate whether a similar concept could be established in Australia.
  - Build new business models in support of CE practices.
  - **Investigate the alignment between designers and contractors**: The designers choose the systems and materials, while the contractors do the actual purchasing. There are some complex dynamics where substitutions by contractors could have a substantial impact on the CE. The roadmap suggested the implementation of a modification register and regular feedback, but further research is required.

Circular economy enablers

- **Technology**
  - **Interoperability issues:** A key limitation in current technology is the lack of interoperability between different systems and tools, hindering seamless data integration and sharing.
  - **Material passport and product passport feasibility:** Improve data availability and tracking of materials (digital product passports).
- **Education**
  - Train certifiers to certify materials for reuse.
  - Train tradespeople and construction workers in the principles of CE.
- **Certification**
  - Specify and assess metrics for certification and reporting.
    - Although industry members may engage in certification and reporting practices, workshop participants expressed concern that current metrics are too general. There is a need to collect and disseminate more specific information about products and services to improve these practices.
    - Commit to meaningful targets for CE in the building sector—not just focusing on reuse and recycling of materials, but also designing-out overconsumption of materials, environmental impacts, decarbonisation, water use, regeneration of nature, lowering the environmental footprint of buildings and social aspects.
    - Partner with companies using the CTI and follow the planetary boundaries.
  - **Integrate social value**: Address the general lack of consideration for social value in circular economy practices, ensuring that sustainability efforts also enhance community and social outcomes.
- **Policy and legislation**
  - Regulatory effectiveness: Investigate existing regulatory requirements for repurposing materials and the impact of individual versus systemic efforts.
    - Green waste is often incinerated or landfilled; more environmentally friendly solutions are needed for its management.
  - New Green Deal: Prioritise construction and real estate which is cost-effective to build and affordable for ordinary citizens.

- Carbon tax or similar mechanism that reduce GHG emissions.
- Research: Proactive planning also needs to be initiated through research to create programs for disaster prone areas to prevent disaster recovery.

APPENDIX

Appendix 1

Australian Architects Declare Climate & Biodiversity Emergency

The twin crises of climate breakdown and biodiversity loss are the most serious issues of our time. Globally, buildings and construction play a major part, accounting for nearly 40% of energy-related carbon dioxide (CO_2) emissions whilst also having a significant impact on our natural habitats. Meeting the needs of our communities and staying within our ecological limits will require a shift in our behaviour as well as the design, delivery and performance of our buildings. Together with our clients, we will need to commission and design buildings, cities and infrastructures as indivisible components of a larger, constantly regenerating and self-sustaining system.

The research and technology exist for us to begin that transformation now, but what has been lacking is collective will. Recognising this, we are committing to strengthen our working practices to create architecture and urbanism that have a more positive impact on the world around us.

We will seek to:

1. *Raise awareness of the climate and biodiversity emergencies and the urgent need for action amongst our clients and supply chains.*
2. *Advocate for faster change in our industry towards regenerative design practices and a higher Governmental funding priority to support this.*
3. *Establish climate and biodiversity mitigation principles as the key measure of our industry's success: demonstrated through awards, prizes and listings.*
4. *Share knowledge and research to that end on an open-source basis.*
5. *Evaluate all new projects against the aspiration to contribute positively to mitigating climate breakdown and encourage our clients to adopt this approach.*
6. *Upgrade existing buildings for extended use as a more carbon efficient alternative to demolition and new build whenever there is a viable choice.*
7. *Include life cycle costing, whole life carbon modelling and post occupancy evaluation as part of our basic scope of work, to reduce both embodied and operational resource use.*
8. *Adopt more regenerative design principles in our studios, with the aim of designing architecture and urbanism that goes beyond the standard of net zero carbon in use.*
9. *Collaborate with engineers, contractors and clients to further reduce construction waste.*
10. *Accelerate the shift to low embodied carbon materials in all our work.*
11. *Minimise wasteful use of resources in architecture and urban planning, both in quantum and in detail.*

In Australia, we as architects are aware that Aboriginal and Torres Strait Islander peoples have long espoused the cultural, social, economic and environmental benefits embedded in the holistic relationship of Caring for Country.

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