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Building materials in a circular economy



From the AHURI Inquiry: Inquiry into housing in a circular economy

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Acronyms and abbreviations used in this report

ABC	Australian Building Control Board	IEA	International Energy Agency
ABD	as-built documentation	IPCC	Intergovernmental Panel on Climate Change
ABM	agent based modelling	ISCA	Infrastructure Sustainability Council of Australia
ABS	Australian Bureau of Statistics	ISSTM	Iron Smelting and Steel Manufacturing Industry
ACCC	Australian Competition and Consumer Commission	LCA	life-cycle assessment
AHURI	Australian Housing and Urban Research Institute Limited	LCC	low-carbon concrete
BPIE	Building Performance Institute Europe	LVL	laminated veneer lumber
CCA	Cement Concrete and Aggregates Australia	MBA	Master Builders Association
CCS	carbon capture and storage	MC	market concentration
CDW	construction and demolition waste	MECLA	Materials & Embodied Carbon Leaders' Alliance
CE	circular economy	MFA	material flow analysis
CI	capital intensity	MS	market share
CLT	cross-laminated timber	MUATCI	Multi-Unit Apartments and Townhouse Construction Industry
CO2e	carbon dioxide equivalent	NASH	National Association of Steel-framed Housing
CRC	cooperative research centre	NatHERS	Nationwide House Energy Rating Scheme
CSI	Cement Sustainability Initiative	NCC	National Construction Code
CSIRO	Commonwealth Scientific and Industrial Research Organisation	NDC	nationally determined contribution
DES	discrete event simulation	NGER	National Greenhouse and Energy Reporting
EE	embodied energy	NHFIC	National Housing Finance and Investment Corporation
EPD	Environmental Product Declaration	NSW	New South Wales
EPiC	Environmental Performance in Construction	OECD	Organisation for Economic Co-operation and Development
EU	European Union	SD	system dynamics
EWP	engineered wood products	UK	United Kingdom
FWPA	Forest and Wood Products Association	UNEP	United Nations Environment Programme
GBCA	Green Building Council Australia	US	United States
GCCA	Global Cement and Concrete Association	WBCSD	World Business Council for Sustainable Development
GHG	greenhouse gas		
HCI	Housing Construction Industry		
HIA	Housing Industry Association		

Glossary

A list of definitions for terms commonly used by AHURI is available on the AHURI website ahuri.edu.au/glossary.

Executive summary

Key points

- **The housing industry is an institution with recognisable ‘rules of the game’ that shape industry structure and actor interactions, which in turn will shape responses to the development of a circular economy (CE) strategy.**
- **Understanding the structure of building-material supply chains is essential for policy development seeking to reduce carbon intensity of new material choice and use in the housing industry.**
- **Housing industry engagement with the CE and reducing greenhouse gas (GHG) emissions by relying less on virgin materials and increasing reuse, recycling and resource recovery will require development of efficient and responsive ‘used’ materials markets.**

Key findings

There has been limited consideration and engagement with circular economy (CE) principles within the residential housing industry and its material supply chains. A starting point for informing the development of a CE is to analyse the institutional arrangements of material supply chains that supply manufactured building materials containing embodied GHG emissions to the residential housing industry. This type of analysis can assist in showing how the housing industry and its supply chains can contribute to reducing GHG emissions by using low-carbon materials and relying less on virgin materials. It can also assist by showing how the industry can close loops by reducing waste through reusing, recycling and recovering resources in the industry and its supply chain.

The material flow analysis (MFA) found that data for tracking material stocks and flows throughout the residential construction sector is inadequate. This applies to new and existing materials as they move into the construction and demolition waste stream. A novel approach was developed, using top-down available datasets and bottom-up generation of data. It showed that the use of concrete continues to increase, which is increasing the carbon intensity of housing. Further, while the number of houses constructed each year has not changed significantly over the past 50 years, the size of houses constructed and the changes in materials have significantly increased the carbon intensity of new housing. The improved understanding of material flows is important for developing an industry CE. The analysis can be extended and improved through the development of better data systems.

Analysis of two sustainable housing developments in Victoria (The Cape and Nightingale Village) highlighted the challenges facing the introduction of CE. Both case studies examined building design and construction, and searched for practices that could be regarded as CE practices. The Cape builders sought to respond to CE principles by facilitating stakeholder collaboration in the design, construction and occupation phases. At the Nightingale Village—while the building life cycle was considered—the emphasis was on reducing costs and meeting environmental objectives by reducing material use. These cases highlight the challenges the industry faces. Some changes were easy, such as brick reuse, while others, such as timber reuse, were constrained by concerns about structural integrity. Also, material reuse was constrained because of the lack of onsite storage space between deconstruction and construction. Further, the cost of disassembly and material reuse incurs costs that builders cannot meet on their own.

The research found through three case-study analyses of material supply chains—concrete, steel and timber—that builders source materials from suppliers without assessing embodied carbon created by manufacture. All three supply chains have local and global features, which means that reducing emissions requires governance arrangements that span multiple jurisdictions. At a global level, high-emission concrete and steel industries have committed to staged emission reductions. Their decarbonisation ‘pathways’ will require significant reinvestment in plant and equipment, product innovation, and change in design and patterns of use in downstream supply chains. Timber use in housing is bifurcated. It continues to be used extensively in detached residential housing. However, its proposed use in the multi-unit apartment industry has stalled. Because the proportion of multi-unit apartment housing is increasing, this means that the carbon intensity of housing as a whole is increasing. Material supply-chain decarbonisation and CE development will require close attention to supply-chain institutional arrangements and collaborative reform supported by broader public policy.

Policy development options

Important policy issues and possible policy responses were identified during the course of the research, which focussed on:

- mapping and analysing the flow of materials into and out of the housing system, and the availability and quality of the necessary data
- design and onsite decisions about material choice and material reuse for low-rise and multi-unit apartment housing construction
- the institutional arrangements of manufactured material supply chains that supply materials to housing industry builders.

The following areas for policy development were identified, and preliminary ideas for their further development are outlined.

- **Materials data collection and analysis:** The research identified significant data gaps that need to be filled if we are to understand the flow of materials used in housing construction; materials already in the housing system; construction and disassembly waste; and reuse. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) has made considerable progress in the development of a data system with its Australian Housing Data Portal. However, further initiatives such as required submission of ‘as-built documentation’ (ABD), and use of ‘material passports’ will vastly improve stock in-use and materials tracking. Data should also be geocoded to support analysis at a regional and local scale.
- **Incentivising disassembly and reuse:** It is difficult for building-industry stakeholders to economically justify disassembly and reuse. Policy development should focus on incentivising disassembly for material reuse, as well as encouraging other ways to reduce embodied energy through material selection and the use of local products. Creating markets for materials reuse within Australia is important, but as many materials and products are imbricated in global supply chains, it is likely that these markets will also be connected to international markets. It is important to ensure that local building-industry actors seeking to reuse materials are not penalised by markets that do not value construction waste.

- **Regulation for low carbon:** The National Construction Code (NCC) is a performance-based code that sets minimum levels for the safety, health, amenity, accessibility and sustainability of buildings. The scope of its sustainability regulation could be expanded to support the decarbonisation of the housing system. It could regulate to require the documentation of embodied carbon in material flows and the reuse of construction and demolition waste (CDW). This regulation could be supported by a simple-to-use digital recording system that records the flow of materials into the housing system. Most regulations on recycling and reuse focus on end-of-pipe solutions for CE. They should also support better measurement of material flows, as well as reuse, rethink, repurpose or remanufacture.
- **Tilting investment flows:** Policy makers can shape investment flows in ways that support the decarbonisation in the materials industries. This form of investment, accompanied by regulation, can support the decarbonisation of materials manufacturing and stimulate demand for recycled materials. Strategic use of public procurement is a complementary form of support. The use of taxation policy can also guide optimisation of resource use across materials life cycles, from resource taxes on raw materials to tax relief on reuse and repair, and creation of carbon credits to incentivise reduced emissions.
- **Building capacity:** Expanding the pool of people with a knowledge of CE is a high priority and requires developments in education, training and skills development. This can be done through curriculum development for use in universities and TAFEs, along with professional development in-service training that presents built-environment embodied carbon and CE concepts. These education and training programs would focus on topics such as materials manufacturing, material supply chains, materials innovation, construction, maintenance and deconstruction processes, building-industry institutional arrangements and emissions reduction policy.
- **Developing low-carbon supply chains:** Building-material supply chains are complex and involve different actors that are often uncoordinated and have conflicting interests. They include manufacturers, distributors, retailers, regulators, professional consultants, contractors and subcontractors. There is a case for establishing housing industry low-carbon supply-chain councils. Council members would be drawn from industry and professional associations, along with civil society social movement organisations, including relevant unions. Each council, supported by a federal government industry agency, would support a deliberative consultative process that prepares plans for the development of low-carbon supply chains for the housing industry.

The study

This research is part of the AHURI *Inquiry into housing in a circular economy* which asked: *How can the transition to a circular economy in housing be implemented to provide more sustainable housing?* The focus of this project (which is one of four projects) presented in this report is on the flow of building materials through supply chains into and out of the residential housing system. These supply chains start with the exploitation of natural resources and CO₂-emitting and other greenhouse-gas-emitting manufacturing industries. The aim of the project was to understand the following:

- The structuring and functioning of the material supply chains supplying manufactured building materials containing embodied GHG emissions to the Australian residential housing industry.
- How the housing industry can contribute to the CE by reducing GHG emissions through reducing waste by reusing, recycling and recovering resources and relying less on virgin materials to close the material flow loop.

The context for this research into building-material supply chains is dynamic, as the mitigation of climate change has become increasingly challenging in a globalised society.

Four features of this context stand out:

- Global and Australian Government commitments to reducing GHG emissions have increased.
- Continuing rapid urban development using manufactured building materials is a major contributor to global GHG emissions.

- There are inadequate responses to growing volumes of waste and disposal, valuing, reusing, reprocessing and recycling of waste across all stages of the dwelling life cycle.
- A fragmented housing industry has limited capacity to create demand for a low-carbon building materials market.

The research was undertaken across three work packages:

- **Work package 1** modelled the stocks and flows of material flows in the Australian residential sector through material flow analysis (MFA), using data from multiple datasets. Some data gaps were filled by 'bottom-up' historical analysis of phases in housing construction through collaboration with an experienced quantity surveyor.
- **Work package 2** evaluated two 'best in class' residential housing case studies. They were selected through a desktop review of recent projects (2017–2021) using CE criteria that identified 82 potential cases. Two cases in Victoria were selected: a low-density development (The Cape) and a medium-density apartment development (Nightingale Village). Semi-structured interviews were undertaken with 13 research participants with deep involvement in the developments. The interviews were supplemented with site visits, photographs and document review. Recorded interview data were transcribed and analysed deductively using key words from the framework created by Potting, Hekkert et al. (2017) to analyse product chain innovation.
- **Work package 3** examined building-material institutional arrangements for products used extensively in housing construction: concrete, steel and timber. Three methods were used. First, academic and grey literatures and websites were reviewed. Second, industry supply chains were mapped using IBISWorld industry reports (Gecz 2019). Third, semi-structured interviews ($n=20$) were conducted with industry insiders who had deep knowledge of their industries. In addition, 15 participants drawn from key actor groups in the building materials and residential housing industry contributed to a practitioner workshop. Participants were sent a paper, *Building materials in a circular economy: Workshop briefing paper* (see Appendix 1), and responded to questions and provocations (see Appendix 1), as well as contributing to an online whiteboard.

1. Introduction

- The Sharm el-Sheikh Implementation Plan at COP27 recognised that the world faces a climate emergency and confirmed that climate change requires urgent action.
- Continuing rapid urban development using traditional manufactured building materials and construction practices is a major contributor to global greenhouse-gas emissions.
- There are inadequate responses to growing volumes of waste across dwelling life-cycle stages: its disposal, value, reuse, reprocessing and recycling.
- The residential housing industry has a limited capacity to create demand for a low-carbon new and reuse building materials market.

1.1 The research

This report is one of four projects examining how the transition to a circular housing economy could be implemented to provide sustainable housing. The transition to a circular economy (CE) from a linear ‘take-make-dispose’ economy, has become a widely discussed topic in both academia and industry since its introduction from policy makers such as in the European Union (EU 2018). Considering the unsustainable approaches within the sector, academics have highlighted that there is an urgent need to shift into a more sustainable framework, with a focus on implementing a CE approach (e.g. Munaro, Tavares et al. 2020; Norouzi, Chàfer et al. 2021; Núñez-Cacho, Górecki et al. 2018; Panteli, Kylili et al. 2018).

The focus of the project is the flow of building materials into and out of the residential housing system. There is a temporal element to this research, as new construction adds new materials to the existing stock, while demolition creates a flow of materials out of the stock laid down in previous eras. From a circular perspective, demolition promotes only downcycling, whereas deconstruction retains value and in some cases, upcycling. All of the materials used to construct the existing housing stock are produced by manufacturing industries that emit greenhouse gases (GHG), and new construction is equally—if not more—GHG-intensive.

This project understands CE as:

a regenerative system in which resource inputs, waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling. (Geissdoerfer, Savaget et al. 2017: 759)

The aim of the project is to understand the following:

- The structuring and functioning of the material supply chains supplying manufactured building materials containing embodied GHG emissions to the Australian residential housing industry.
- How the housing industry can contribute to the CE by reducing GHG emissions through reducing waste by reusing, recycling and recovering resources and relying less on virgin materials to close the material flow loop.

Each of the four research projects contributing to the wider AHURI *Inquiry into housing in a circular economy* were guided by five research questions:

1. Who are the key institutional actors in the supply chain supplying materials for use in the Australian residential housing system?
2. What supply-side/demand-side drivers can increase the contribution that materials production and distribution can make to a CE?
3. What are the needs and opportunities for training and Australian jobs in the creation of the materials supply chain within a developing CE?
4. What are the key innovation challenges and opportunities from Industry 4.0 and the use of materials in the Australian residential housing system?
5. What are the challenges and opportunities—financial, fiscal, regulatory and policy—for material use resulting in more sustainable design and build outcomes?

This section presents an institutional analysis of the residential housing industry, before discussing the policy context and challenges. This is followed by an overview of CE and construction industry research and the research methods applied in this project.

1.2 The housing industry as an institution

The housing industry is an institution, and understanding the housing system requires recognising its ‘rules of the game’. These are the ‘humanly devised constraints that shape human interaction … and structure incentives in human exchange, whether political, social or economic’ (North 1990: 3). These ‘rules’ will shape actor interactions, exchanges and responses throughout the development of a CE strategy. It is important, as the Building Performance Institute Europe (BPIE) argue, to recognise actor groups and their supply chain relationships (De Groote and Lefever 2016). Further, because innovation in the Australian housing industry is slow and geographically differentiated (Böhme, Escrivano et al. 2018; Crommelin, Sian et al. 2021; Shergold and Weir 2018) developing and implementing a CE strategy will not be uniform and will take time. This is similar to other countries (GlobalABC/IEA/UNEP 2020).

A CE housing system will require businesses to coproduce change in the ‘rules’ applied to projects, contracts and subcontracts. How they might coproduce new ‘rules’ can be thought about by recognising that businesses persist over time, change and continue to perform. The structure-conduct-performance (SCP) heuristic, used to inform research into the economics and strategy of industrial organisations (Matjjas 2014; Schmalensee 1987), can help understand how housing industry and material supply chains businesses might do this.

Structure refers to variables, such as:

- buyers and suppliers
- barriers to entry
- product differentiation
- vertical integration
- industry concentration
- diversification.

Conduct refers to agentic strategy, such as:

- strategic planning
- R&D
- pricing
- investment
- product choice
- mergers
- takeovers.

Performance refers to measures, including price, profit, efficiency, innovation and product quality.

SCP research raises questions about the extent to which industry structure determines company outcomes, or whether the conduct of actors matters. Some find in favour of determinist structural explanations. Others argue for more constructivist explanations based on the agentic conduct of actors within businesses. Mosca (2016) argues that conduct is the most important element because it draws attention to firm strategy. 'It is firms' conduct that has the pivotal role: it affects both performances and market structures' (2016: 301). In other words, structure shapes strategy but does not determine strategy, because the conduct, or agency, of people in businesses matters. Remembering that agency is possible is important when major industry change, such as CE, is on the agenda.

The Australian housing construction industry has a recognisable structure. Recognising the key features of this structure should help in assessing the capacity of industry businesses to strategise and begin coproducing CE initiatives. Two dimensions of this structure are now explored: housing industry arrangements and intermediary organisations.

1.2.1 The housing industry core

The core of the Australian housing industry has six defining structural features¹. It:

- has two distinct parts that build different types of housing
- is dominated by geographically dispersed small builders
- has low capital intensity (CI)
- has low market concentration (MC)
- has low innovation and barriers to entry
- responds on the demand-side to individual purchasers.

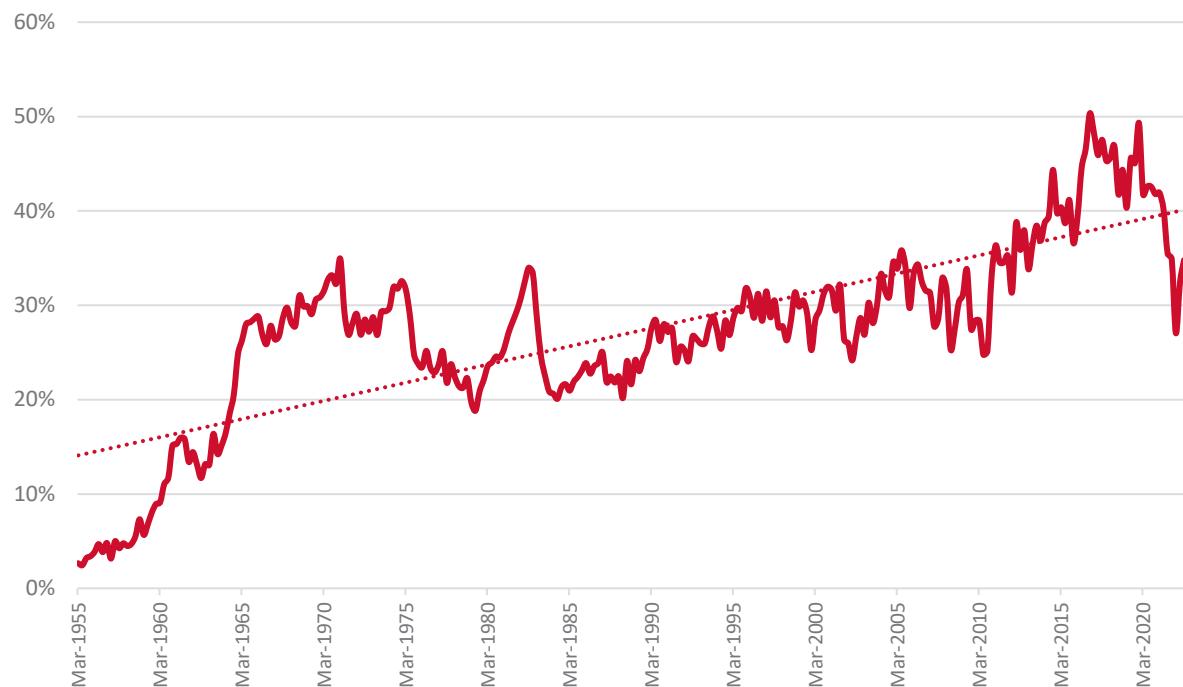
¹ This summation of structural features is drawn from earlier AHURI research (Dalton, Horne, et al. 2013; Dalton, Hurley, et al. 2013; Ong, Dalton et al. 2017; Rowley and Phibbs 2012) and IBISWorld industry reports (Kelly 2022c, 2022b).

The Australian housing industry has two distinct sectors:

- the Housing Construction Industry (HCI) produces detached houses
- the Multi-Unit Apartments And Townhouse Construction Industry (MUATCI) produces multi-unit apartments and townhouses.

The two sectors produce different physical structures and use different institutional arrangements to design, finance, build and market new dwellings. Further, the spatial distribution of houses and apartments is different. Most new houses are built on subdivided land rezoned from rural to urban on the city fringe, whereas most apartments are built on inner and middle ring land and replace earlier residential, commercial or industrial land uses. In recent decades, the share of townhouses and apartments being built, presented as 'other residential' in the ABS data, has increased and the share of houses has decreased (Figure 1).

Figure 1: 'Other residential'² dwelling completions as a proportion of total dwelling completions: actual and linear trend: 1955–2020



Source: ABS (2023) 8752.0 *Building Activity Australia*, Table 37, Number of dwelling unit completions by sector, Australia.

² 'Other residential' in this series consists of three sub-categories of dwellings that feature in denser forms of housing provision in the inner areas of Australian cities. The categories are: Semi-detached, row or terrace houses, townhouses; Apartments; and Residential buildings not elsewhere classified.

Both dwelling-construction industries are dominated by geographically dispersed small builders and a smaller number of larger builders. Both use a 3 to 4 per cent cashflow business model to assess and agree contracts:

- HCI builders work with land developers who subdivide land, provide infrastructure and produce land lots for new houses.
- MUATCI builders work with developers who own land, design projects and arrange construction loans.

Both industries are highly competitive. Builders in both industries rely on skilled trade-based subcontractors, which may be companies, partnerships or sole traders. They have continuing arrangements with material suppliers, land and property developers and financial institutions. Both industries experience volatility due to factors like changing purchaser demand, migration, interest rates, labour availability and government programs.

Industry structure can be assessed by focussing on four measures:

- capital intensity (CI)
- market concentration (MC)
- innovation
- barriers to entry.

CI measures the relationship between capital stock and wages. Both dwelling-construction sectors have a low CI ratio due to the high proportion of resources used to engage skilled labour. MC measures industry competition by testing for oligopolies. MC in both dwelling-construction industries is low. Innovation is measured by the uptake of patents, software and improved materials and technology. Both HCI and MUATCI sectors are increasing their use of software, but innovation is otherwise low to moderate. Barriers to entry prevent new competitors from entering the industry. Barriers to entry in both industries are moderate and stem from government regulatory requirements, including registration, insurances, industry association membership and market conditions.

Individual owner-occupiers and private-rental landlord investors purchase most HCI and MUATCI dwellings. Social-housing providers and build-to-rent companies commission or purchase very small numbers of dwellings. First homeowners buying housing on the urban fringe, often assisted by first homeowner grants, are a significant HCI purchaser group (Taylor and Dalton 2015). More recently, first homeowners have become a more significant MUATCI purchaser group. Private-rental landlord investors are a significant demand group for MUATCI, but less significant for HCI. During the early postwar decades, HCI builders built housing estates for state housing authorities (SHAs) (Howe 1988). From the mid-1980s, social-housing procurement of HCI and MUATCI dwellings declined and has remained low (Troy 2012). Table 1 provides further detail on the structure and operations of the two industries.

Table 1: The housing construction industry: houses and apartments

Industry features	House construction industry (HCI)	Multi-unit apartment and townhouse construction industry (MUATCI)
What is produced	<p>Products as a share of 2022 \$75.1 bn industry revenue:</p> <ul style="list-style-type: none"> • New houses: 58.8% • Alterations, additions, renovations: 20.4% • Repairs and maintenance: 13.8% • Other services: 7.0% 	<p>Property developers own the land and contract with building construction companies to construct strata-titled multi-unit apartment buildings and townhouses.</p> <p>Products as a share of 2022 \$40bn revenue:</p> <ul style="list-style-type: none"> • Townhouses and semi-detached terraces: 39.2% • High-rise and super-high-rise apartments: 27.3% • Medium-rise (4–8 storey) apartments: 27.8% • Low-rise apartments (1–3 storey): 5.7%
Who purchases housing	<p>Purchaser segments and shares of 2022 \$67.1bn industry revenue:</p> <ul style="list-style-type: none"> • Private homebuyers: 62.2% • First-time homebuyers: 30.1% • Developers/speculators: 6.2% • Public sector agencies: 1.5% 	<p>Purchasers are owner-occupier households and landlord investors. They contract to purchase an apartment from an apartment developer using a 'pre-sales' contract. Sufficient demand is indicated by the level of 'pre-sales'. Developers obtain construction loans and contract builders construct apartments and townhouses.</p>
Who produces housing	<p>Small business builders produce small numbers of houses. Larger builders known as 'volume builders'—such as Metricon, G.J. Gardner Homes, ABN Corporate Services, BGC Housing Group, Simonds Group, Burbank, Henley Homes, Hotondo Building—have market shares ranging between 1% and 3% of new construction. These companies are extending the geographic spread of their operations. Both the small builders and the volume builders rely on subcontracting, with little direct employment.</p>	<p>Small-scale businesses dominate the industry. Over 75% of industry enterprises are small businesses with no paid employees and are operated by sole proprietors or partners. Approximately 75% of businesses generate less than \$200,000 in annual revenue. The industry includes some large-scale multi-unit builders such as Multiplex, Dyldam, Hickory Group, Lendlease, Meriton, L U Simon, Parkview Construction, J Hutchinson. They have market shares ranging between 2% and 5% of annual apartment production, totalling 28%. All builders rely on extensive subcontracting and little direct employment.</p>
Industry structure	<p>Low capital intensity: builders provide project management and trade skills and typically lease capital equipment, such as scaffolding and earthmoving equipment. Builders rely on subcontractors who provide their own tools.</p> <p>Low concentration: house construction broadly divides into two categories:</p> <ol style="list-style-type: none"> a. many small-scale businesses with half generating less than \$200,000 pa, and 55% of businesses with no permanent employees consisting mainly of sole proprietors and partners b. 30 medium-scale to large-scale firms (the volume builders listed above) each constructing more than 400 dwellings pa, using subcontract labour with annual revenue exceeding \$50 million. <p>Low/moderate innovation: development of materials and tools has reduced skilled labour requirements and project managers are increasing their use of digital tools.</p> <p>Barriers to entry: builder registration, licence to practice, member of industry associations with access to insurance, subcontractors and arrangements with material suppliers.</p>	<p>Low capital intensity: the main industry contribution to value comes from skilled labour and construction management services that do not require significant capital. Project capital is typically the responsibility of the developer.</p> <p>Low concentration: the industry's four largest firms were expected to account for less than 20% of industry revenue in 2020–21, although the share has increased.</p> <p>Low/moderate innovation: increasing use of digital technology in project management and innovative building materials.</p> <p>Barriers to entry: builder registration, licence to practice, member of industry associations with access to a pool of subcontractors and arrangements with material suppliers.</p>

Source: Dalton et al. (2011), Dalton, Hurley et al. (2013); Kelly (2022a, 2022b); Ong, Dalton et al. (2017).

1.2.2 Intermediaries in the broader field

Intermediaries are organisations that represent service members, and mediate, translate and transfer knowledge between actor groups. There are many intermediary organisations advocating for the mitigation of climate change by establishing more sustainable socio-technical systems (Ehnert, Egermann et al. 2021; Kivimaa, Boon et al. 2019; Moss 2009). In the more prosaic context of the Australian housing industry, three main types of intermediary organisations can be identified: industry associations, professional associations, and civil society social movement organisations. Table 2 presents a list of intermediary organisations that seek to shape the way the built environment is designed, procured and constructed.

Table 2: Housing industry intermediaries

Industry associations	Professional associations	Civil society social movement organisations
Housing construction		
<ul style="list-style-type: none"> • Housing Industry Association • Master Builders Association • National Association of Steel-Framed Housing 	<ul style="list-style-type: none"> • Australian Institute of Architects • Planning Institute of Australia • Engineers Australia • Australian Institute of Project Management • Australian Institute of Building Surveyors • Australian Institute of Quantity Surveyors • Australian Institute of Building • Building Services Contractors Association of Australia • Building Designers Association of Australia • Facility Management Association of Australia 	<ul style="list-style-type: none"> • Green Building Council of Australia (GBCA) • Australian Sustainable Built Environment Council • Alternative Technology Association • Beyond Zero Emissions • Renew • Materials & Embodied Carbon Leaders' Alliance (MECLA) • Energy Efficiency Council • Infrastructure Sustainability Council of Australia (ISCA) • market forces
Land development		
<ul style="list-style-type: none"> • Urban Development Institute of Australia 		
Construction		
<ul style="list-style-type: none"> • Australian Construction Industry Forum • Australian Constructors Association • Civil Contractors Federation • Construction & Mining Equipment Industry Group 		
Property		
<ul style="list-style-type: none"> • Property Council of Australia • Real Estate Institute of Australia 		

Source: Authors

Industry associations are member organisations that represent and service businesses. They consult and shape the way members understand their industry, develop strategy, collaborate and compete. Industry associations do this through working groups, committees and conferences, and through establishing endogenous and exogenous industry relationships. Parallel to these collaborative processes, member businesses continue to compete with each other. The industry associations that represent the core of the housing industry are the Housing Industry Association and the Master Builders Association. They both have large memberships that reflect the interests of the small number of larger builders and the larger number of small builders and subcontractors that are in the HCI and MUATCI parts of the industry.

Some national industry associations are members of international associations. This is the case for some material manufacturing industries with global operations supplying materials to Australian residential building businesses. Notable materials in this category are steel, aluminium and concrete, which are carbon-intensive materials and are produced in Australia by oligopolistic globalised industries (GCCA 2021; IAI 2021; WSA 2021).

Built-environment professionals—including architects, engineers, quantity surveyors and project managers—provide services to both dwelling-construction industries. These people are members of professional associations that contribute to defining and regulating the professional knowledge base, education and training, membership eligibility and codes of ethics (Larson 2012). Connected to this form of self-governance, some built-environment professions have committed to mitigating climate change (AIA 2022; Baikie 2021a; EA 2021). For example, Engineers Australia (EA 2021) state that ‘engineers must be at the forefront in policy formulation and decision-making affecting the scoping, planning, design, delivery and operation of systems for climate change mitigation and adaptation’.

Civil society social movement organisations act as intermediary organisations by advocating on built-environment climate change issues. They can be councils, associations, alliances and institutes. Supported by research, they direct advocacy at companies, financial institutions, industry associations, governments and public sector agencies, and press for change in investment and regulation. Some organisations run sustainable buildings voluntary certification programs that are 'rule regimes that seek improved sustainable building development and use and that provide rewards to rule-takers who voluntarily commit to these' (van der Heijden 2017: 57). Two prominent certification schemes are:

- NABERS—which offers Carbon Neutral Certification for many building types (NABERS 2023)
- Green Building Council of Australia (GBCA) Green Star Homes rating system for volume home builders—which sets a higher standard than that required by the National Construction Code (NCC) star-rating system.

1.3 Policy context and challenges

1.3.1 Policy context and challenges

The context for this research into building-material supply chains is dynamic, as the mitigation of climate change has become a priority nationally and internationally. Recent COP conferences and multi-state agreements are important markers of international acknowledgment of the need to act (The Treasury, ND; United Nations 2022). Nationally, recognition of climate change and mitigation as a policy priority was signalled in June 2022 when the Australian Government lodged an updated Nationally Determined Contribution (NDC) with the United Nations Framework Convention on Climate Change secretariat for a more ambitious GHG reduction target. This is the context for identifying four policy areas that present challenges for the development of a CE in Australia specifically related to the residential housing sector.

- GHG emission reductions
- Urbanisation and resource use
- Reducing urban carbon emissions and institutional capacities
- Regulating for CE.

1.3.2 GHG emission reductions

The revised NDC GHG emission-reduction target was agreed to at a national level and registered at an international level. It commits to reducing GHG emissions by 43 per cent below 2005 levels by 2030, which is a 15 per cent increase on Australia's previous 2030 target. Accompanying the new target, the Clean Energy Regulator will be required to regulate for GHG emissions reductions by companies by increasing the 'baselines for each facility in close consultation with industry' (Australian Labor Party 2021). Currently, the National Greenhouse and Energy Reporting (NGER) Scheme requires companies to be listed if their combined Scope 1 and Scope 2 annual GHG emissions are equal to or greater than 50 kt CO₂ equivalence (CO₂-e) (Clean Energy Regulator 2022). However, NDCs can only be achieved if the contributions of firms in high-emitting industry sectors are recognised, and reduction targets are set and met by these firms. The development of the detailed policy framework for determining these contributions is in progress (DCCEEW 2022).

Globally the construction industry is responsible for almost 50 per cent of the worldwide annual resource consumption (OECD 2019). In 2011, 37 gigatonnes of non-metallic mineral materials were extracted, with an expected increase to 86 gigatonnes by 2060 (Meglin, Kytzia et al. 2022). An average of 1.68 kilograms of construction and demolition waste (CDW) is produced per person per day, which can be used as secondary building material (Kaza, Yao et al. 2018). In 2018, the building and construction sector accounted for 36 per cent of final energy use and 39 per cent of energy and process-related CO₂ emissions—11 per cent of which resulted from manufacturing materials and products such as steel, cement and glass (Circle Economy 2019). This situation is placing the global natural environment under pressure (OECD 2020).

In Australia the construction industry, which includes the housing industry, is also a high-resource use industry, and it is important that this resource use and resulting emissions are recognised and mitigated. In 2013, the construction sector as a whole was responsible for 18.1 per cent of Australia's carbon footprint, when using CO₂-e embodied emissions by final demand as the measure (Yu, Wiedmann et al. 2017). Residential building construction contributed 21.5 Mt CO₂-e emissions, which formed a 23.7 per cent share of total construction embodied emissions. Buildings contribute to the carbon footprint through their operation, through embodied carbon emissions from materials and construction, and through end-of-life or deconstruction (Gosling, Towill et al. 2015).

Currently, the embodied carbon from buildings contributes to a 16 per cent share of the whole-of-life building carbon emissions (GBCA 2021), with the remainder coming from operational carbon emissions. However, as the grid decarbonises and building energy efficiency improves, the embodied carbon share is expected to grow to 85 per cent by 2050 (GBCA and thinkstep-anz 2021: 4), highlighting the importance of lowering the carbon intensity of buildings. Strategies such as specifying lower-emodied carbon materials, materials with efficient design, designing for deconstruction and looping of materials and minimising CDW waste following deconstruction will contribute to developing a CE housing sector so it contributes proportionately to meeting the Australian 2030 NDC.

1.3.3 Urbanisation and resource use

Globally, urbanisation continues to increase the share of GHG emissions. In 2015, emissions attributed to urban areas were estimated to be 25 GtCO₂-e (about 62% of the global share); and in 2020, 29 GtCO₂-e (67–72% of the global share) (IPCC 2022). As urban populations grow, the demand for housing will increase. Typically, new housing and infrastructure are built with steel, concrete, bricks, asphalt, aluminium, plastic and glass. These materials have high levels of embodied CO₂. Timber is also used in housing construction and is recognised as a low-carbon or carbon-negative material. However, the future mix in materials use is uncertain. This focus on urbanisation changes the policy context for material and GHG-producing industries. The Intergovernmental Panel on Climate Change (IPCC; 2022: 11-6) observed that until recently 'industry has so far largely been sheltered from the impacts of climate policy and carbon pricing due to concerns for competitiveness and carbon leakage'.

Australia follows the broader global trend of continuing urbanisation, and for many decades has been one of the most highly urbanised countries in the world. By 2016, almost 90 per cent of the Australian population lived in urban areas. Further, the population is also concentrated in capital cities, which held 67 per cent of the population in 2021 (ABS 2022a). A key driver of this growth has been immigration. In 2020, 30 per cent of the Australian population of nearly 26 million were born overseas. The underlying assumption is that population growth will continue. Infrastructure Australia is working on a forecast that over 'the next 30 years, Australia will grow by an additional 10 million people' (Colacino 2018). More broadly there is consensus that continuing urban growth, especially in the larger capital cities, will underpin continued economic growth.

Closely associated with continued urban growth is the production of CDW. Typically, buildings have a construction, retrofit, demolition and redevelopment life cycle which produces CDW. One measure of CDW is dwelling demolitions: in the five years to March 2021, 107,294 dwellings were approved for demolition (ABS 2021b). Building demolitions produce CDW that consists of various materials such as concrete, bricks, plaster, timber, wood, glass, metals and plastic. In the European Union (EU) CDW accounts for more than a third of all waste. In Australia, approximately 27m tonnes of CDW per annum is created, which constitutes approximately 44 per cent of all waste. Of this, approximately 50,000 tonnes is litter or illegally dumped, 6.3m tonnes goes into landfills, and 18.7m tonnes is recycled into road base (Pickin, Wardle et al. 2020).

The challenge is to develop policies that ensure that CDW becomes a resource not waste, as per the CE framing. In Australia, *The National Waste Policy Action Plan* (NWAP) sets a target for achieving an 80 per cent average resource recovery rate from all waste streams; along with increasing the use of recycled content (Australian Government 2019). Also, the challenge is to ensure that CDW has the highest possible reuse value, so that energy consumed in lower-level reuse is minimised. Too often CDW use is downgraded to recycling or used for energy generation. However, the impediments to recycling CDW are entrenched. Park and Tucker (2016) nominate four main institutional barriers:

- the cost of materials reuse is higher than using new materials
- the lack of an established market for reuse of CDW materials
- the institutionalised reluctance to use available technological and practical knowledge to reduce CDW
- the broad perception that Australia has abundant supplies of natural resources.

A key feature of rapid urban growth in Australia is the recurring policy consensus that the supply of new housing is not responding sufficiently to population growth and household formation. It is evident in the establishment of advisory bodies such as the Indicative Planning Council for the Housing Industry (1975–1977) (Milligan and Tiernan 2011), National Housing Supply Council (2008–2013) and the announced National Housing Supply and Affordability Council (Parliament of Australia 2023). It is also evident in recent AHURI research agendas and reports (Gilbert, Rowley et al. 2020; Gurran, Rowley et al. 2018; Ong, Dalton et al. 2017; Rowley, Gilbert et al. 2020). More recently, NHFIC (2021) has reported on demand and supply issues. Running alongside the policy focus on housing supply there have been approximately three decades of urban planning policy aimed at densifying inner-city areas that ‘have changed and concentrated population in our cities’ (Coffee, Lange et al. 2016). Figure 1 presents data on the increasing proportion that multi-unit dwellings have formed of all new dwelling completions for the period 1955–2021.

This denser housing, the available evidence suggests, is leading to an overall increase in the carbon intensity of the housing stock as the proportion of detached housing of total new housing declines and the proportion of apartment housing increases. The predominant form is mid-rise and high-rise multi-unit apartments built on land cleared of earlier residential, industrial or commercial buildings. A bottom-up modelling study of five housing types in Victoria—brick veneer, double brick, timber, precast concrete and reinforced concrete—compared the OE (heating and cooling energy), embodied energy (EE) and total life-cycle energy (LCE) for each housing type (Li, Foliente et al. 2021). Its headline finding was that at the building level, the average EE, OE and LCE intensities for apartments are higher than for the houses (Li, Foliente et al. 2021). This difference was attributed to the construction type and materials used, as apartments are built from concrete whereas houses are built mainly of brick veneer, timber and double brick, which have lower EE intensities than concrete³.

1.3.4 Reducing urban carbon emissions and institutional capacities

If embodied carbon emissions and CE development are to become features of the housing industry, its institutional arrangements must be recognised. An already noted feature is that the housing industry has two distinct parts—HCI and MUATCI—that produce different types of housing with distinct geographies, using different arrangements to design, finance, build and market dwellings. Also, both dwelling-construction industries are comprised of a large number of small builders and a small number of large builders. However, builders build dwellings that are, in the main, not standard products. Another feature is the extensive use of subcontracting, which can be understood as a way in which builders share, mitigate and shift the many risks that are integral to the design, financing, procuring and building of housing (Bosch and Philips 2003; Riazi, Zainuddin et al. 2020). These are the features that have led to the dwelling-construction industry being described as a ‘fragmented’.

Establishing a housing industry CE in the production of the built environment will require reworking the ‘rules of the game’. Three areas stand out for some reworking: material and service supply chains; worker skills and capacities; and digitalisation for sustainability.

³ It is important to note that sustainability arguments are made for increasing urban housing densities by facilitating multi-unit and high-rise apartment development through urban-planning provisions. The arguments typically made in support of densification of housing are that it curbs sprawl, reduces GHG emissions by supporting public transport and walkability, improves housing affordability and choice, encourages active streets and social mix, and provides opportunities to apply design standards that create dense desirable urban neighbourhoods (Hurley, Taylor et al. 2017). To the extent that urban densification creates these outcomes, it can be argued that a higher EE, EO and LCE can be traded off against other sustainability outcomes.

Material and service supply chains

In an era where the policy imperative is to reduce carbon emissions, the redesign of supply chains has become a research focus (Bressanelli, Perona et al. 2018; Sarkis 2019). This literature advocates for new forms of strategic conduct by businesses by ‘looping’ supply chains so that materials and goods are brought back into the forward supply chain. Bressanelli, Perona et al. (2018: 7395) look for ‘challenges that may hamper a supply chain redesign’; Shi, Zhang et al. (2018) examine the way firms in supply chains shape sustainability outcomes; Rezaei (2019) considers how to develop criteria for selecting suppliers that support sustainability objectives; and Isaksson, Johansson et al. (2010) examine the relationship between supply-chain innovation and sustainable development. However, the challenge is how research of this nature might inform the development of housing industry CE strategies.

Supply chains are systems in which businesses are located, and facilitate the production, procurement and delivery of products and services. A business will typically have upstream connections supplying materials and products, and downstream businesses receiving outputs. Firms in supply chains vary in size, command over resources, and their capacity to change the way they do things. The challenge for the housing industry is to consider how this research might be used, by recognising three key features.

First, builders procure materials and services from businesses in approximately 27 industries (listed in Appendix 4). They do this as they build a house or apartment block by following a procurement script presented in the documentation prepared by professionals, which includes designers, architects, engineers and quantity surveyors. Each business that a builder procures from is a participant in a supply chain with distinctive features, and they vary greatly in terms of their structure, competition, geography and capital-to-labour cost ratios.

Second, there can be pull or demand-side pressures that originate with consumers and their builders, such as certification schemes. For example, the GBCA Green Star Homes Certification scheme based on energy use, health and water-use standards. Conceivably this scheme could be expanded to require accounting for embodied carbon in materials by requiring other CE measures, such as management of waste, designing for disassembly and use of recycled materials.

Third, push or supply-side pressures can be exerted along material supply chains by large global companies with R&D and innovation capacities. For example, companies in the concrete and steel industries promoting the use of Environmental Product Declarations (EPDs) that provide environmental data based on the life-cycle assessment (LCA) of their materials (BlueScope 2021a; 2021b; Boral Limited 2020).

Worker skills and capacities

Movement towards a more resource-efficient and circular economy will change economic activity and patterns of employment—particularly in the materials-intensive industries (Laubinger, Lanzi et al. 2020). Inevitably there will be tensions about CE and labour-market change (Dufourmont and Brown 2020). Some of these changes and tensions can be assisted by distinguishing two main types of ‘circular’ jobs:

- **Core circular jobs** are directly engaged in working with materials and processes such as renewable energy, repair, managing waste and supporting reuse.
- **Enabling circular jobs** are engaged in creating and expanding CE through management, designing and digitising (Burger, Stavropoulos et al. 2019).

In the materials-intensive industries that currently manufacture new materials, it’s possible that there will be a decline in output and employment. However, this decline could be accompanied by growth in employment that extends the life of materials through reuse (Laubinger, Lanzi et al. 2020: 18; Llorente-González and Vence 2020).

It is not clear yet how CE-driven economic and employment change will develop within the Australian housing industry. To date, economic and employment analyses of a shift to CE arrangements—such as those outlined in the paragraph above—are economy-wide or high-level sectoral analyses. Nevertheless, the introduction of CE will require labour-market changes in the housing industry and its material supply chains. It will start by identifying and implementing measures that may, within an agreed time frame, achieve carbon-reduction targets for new housing and major housing retrofits. These measures include:

- increasing reuse and retention
- building less and dematerialising building elements
- building smarter by using lowest carbon building systems and elements and offsite prefabrication
- sourcing lowest embodied carbon materials from the many industry supply chains (Prasad, Kuru et al. 2021: 38).

Digitalisation for sustainability

A significant challenge facing the housing industry, and the construction industry more generally, is the use of digital technology in building construction. This industrial use of technology is often referred to as Industry 4.0. The evidence suggests that the take-up of Industry 4.0 in the construction industry has been partial and slow (Hasan, Elmualim et al. 2018; Leviäkangas, Mok Paik et al. 2017; Newman, Edwards et al. 2020; Perera, Jin et al. 2021). Multiple benefits can be realised through greater use of Industry 4.0 (see Appendix 3), including greater realisation of sustainability objectives (Müller, Kiel et al. 2018). There are two distinct benefits for the construction industry. Industry 4.0 can be used to:

- measure the carbon footprint of materials and products used to create new buildings or to undertake significant retrofits (BPIE 2021)
- create accurate, systematic and easily accessible ‘track and trace’ systems, as well as digital building records that can be used by owners, users and emergency services to find out how their building is constructed and what utility services have been installed (Shergold and Weir 2018).

The EPD system that some material manufacturers have developed is a starting point for measuring the carbon footprint of buildings. When fully developed, it will be able to support a full building-level assessment of embodied carbon. However, two preconditions have to be met before this can be done.

First, there has to be an agreed system for undertaking and registering EPDs. Such a system, albeit a voluntary system, has been established by EPD Australasia. It registers and publishes EPDs that are verified to ISO 14025. Building and construction products are assessed against the European standard EN 15804.

Second, there has to be a requirement—such as that recommended by Shergold and Weir (2018)—for each building to have an up-to-date building manual that contains data including ‘as-built documentation’ (ABD), fire safety system details and maintenance requirements and conditions of building use. However, Perera, Jin et al. (2021) found in their research, *Digitalisation of Construction*, that it is not standard practice for NSW builders to produce and lodge an ABD.

1.3.5 Regulating for a circular economy

Built-environment regulation in its earliest forms supported broader health, safety and environmental public policy objectives, and the form of Australian cities reflects this history of regulation. It has been accompanied and supported by the development of arrangements between many state and non-state actors. Black (2002: 26–27) sums up this way of understanding regulation as a social and cultural product:

Regulation is an activity that extends beyond the state, thus regulation may on the basis of such a conceptualisation embrace a variety of forms of relationship between state, law and society. It thus enables the identification, creation and analysis of regulatory arrangements that involve complex interactions between state and non-state actors, and enables each to be identified as both regulators and regulatees.

The contemporary challenge in Australia is for actors to further develop ways to mitigate climate change through the regulation of building construction. In particular, it will require measures that support actors to govern embodied carbon stocks and flows into and out of the housing system. In this way, the housing industry will be required in future to contribute to reducing the carbon footprint of buildings. However, the current system of building regulation has institutional features that must be acknowledged and worked with if the development of an additional carbon-reduction mitigation capacity is to be incorporated into the National Construction Code (NCC).

In Australia, building regulation has two key features. First, like much Australian governance, responsibility is shared between state and territory governments and the federal government. This system is the outcome of a process over many decades where a national government agency, the Australian Building Control Board (ABC 2023), established under an intergovernmental agreement, is responsible for the NCC that provides:

the minimum necessary requirements for safety and health; amenity and accessibility, and sustainability in the design, construction, performance and liveability of new buildings (and new building work in existing buildings) throughout Australia.

The states and territories have flexibility in the implementation of the NCC through their administrative arrangements.

Second, the NCC includes a sustainability objective, which flowed on from when sustainability was included as an objective in the Building Code of Australia, a 2007 iteration of the NCC (Meacham 2016). However, the sustainability regulation has been fraught because of housing industry resistance to minimum standards (Crabtree and Hes 2009; Moore, Berry et al. 2019). From the 1970s, state and territory governments promoted voluntary initiatives on energy efficiency, and it was not until 2003 that energy efficiency standards were mandated for houses, and until 2005 for multi-residential developments. Subsequently, requirements were increased, and in 2010 the 6-star standard was adopted. In 2022, new NCC standards for energy efficiency, condensation management and liveable housing commenced, which raises the energy star rating from 6 to 7 stars in 2023.

Although limited, research nevertheless shows that the energy efficiency standards required by the NCC have changed the way houses are designed and constructed. There have been energy savings for households in new homes (Berry and Marker 2015). Underpinning this has been the Nationwide House Energy Rating Scheme (NatHERS) software tool used to assess plans and building specifications, which has resulted in better insulation, double-glazed windows, shading, sun-smart dwelling orientation and solar panels.

1.4 Research methods

The research presented in this report was undertaken across three work packages. The methods used in each work package are briefly described.

1.4.1 Stocks and flows modelling

The methodologies used to define, map and estimate built-environment material stocks and flows vary considerably, and there are choices to be made about how best to estimate flows. However, Augiseau and Barles (2017) provide some guidance about how to assess these methodologies by arguing that four key concepts can be discerned, and recognising them assists in understanding material stocks and flows in and out of the built environment.

Augiseau and Barles distinguish between ‘bottom-up’ and ‘top-down’ methodologies. *Bottom-up analyses* start by focussing on the way materials circulate or flow at the local level. They do this by analysing existing stocks and differentiating types of stock and establishing categories. *Top-down analyses* of material use are undertaken by summing the inflow and outflow of materials by either adding to or subtracting from the estimated stock.

Augiseau and Barles then distinguish between 'static' and 'dynamic' analyses. The study of stocks and flows also vary in the way they account for time. *Static approaches* are limited to short periods of time, and are used to produce snapshot-type analyses. *Dynamic analyses* use longer time frames and include assumptions about 'end-of-life'. The use of longer time frames and a focus on end-of-life is important for this research, as most housing is used over many decades. As a rule of thumb, the average expected lifespan of a house is at least 60 years.

A mixed-methods approach was used in this research to model residential housing stocks and flows. This involved reviewing the modelling literature and identifying data sources that could be used to model residential housing system material stocks and flows. Approaches to analyse residential housing materials stocks and flows were reviewed to identify feasible and suitable approaches. Table 3 presents a summary of four commonly used methods.

Table 3: Main simulation modelling methods used in stock and flow analyses

Method	Time treatment	A system is modelled as	Abstraction level	Example applications
Discrete event simulation (DES)	Dynamic-discrete	... a sequence of operations	Low	Manufacturing, service systems, healthcare, etc.
Agent based modelling (ABM)	Dynamic-discrete	... interacting agents	Low–high	Population, pedestrian, road traffic and epidemiology modelling. (Or whenever the focus is on individual objects and their local behaviour and interactions)
System dynamics (SD)	Dynamic-continuous	... stocks, flows, rates, feedback loops, etc.	Medium–high	Strategic management, marketing and macroeconomic issues, ecological and social systems
Material flow analysis (MFA)	Static-(quantified)	... processes, stocks, and flows	High	Industrial ecology, urban/social metabolism

Source: Authors

The research objective was to produce a high-level model of the stocks and flows of materials for houses in the broader Australian residential housing market. This requires a high level of abstraction. Hence, discrete event simulation (DES) was judged unsuitable. Agent based modelling (ABM) and system dynamics (SD) were also considered by the research team. However, the use of these techniques was precluded because the data required either does not exist, are incomplete or insufficient. A database was required that captures the composition of buildings long-term in order to optimise the information flow across the supply chain and to better coordinate supply of and demand for various construction material. However, it was decided that the available data and additional data that could be derived from a bottom-up analysis of the stock would support a material flow analysis (MFA).

MFA systematically assesses flows and stocks of materials within a system defined in space and time. It connects the sources, the pathways, and the intermediate and final sinks of a material. Because of the law of the conservation of matter, the results of an MFA can be controlled by a simple material balance comparing all inputs, stocks and outputs of processes. It is this characteristic of MFA that makes it attractive as a decision-support tool in resource management, waste management and environmental management (Brunner and Rechberger 2016).

The required components of an MFA are system boundaries, processes, stocks and flows. First, system boundaries are identified, including the material for which the system is quantified, the time interval, and the geographical scope of the study. Second, the system variables, comprised of processes, stocks and flows are named and quantified. A process is defined where material is transformed, stored or distributed. Stocks, within each process, show the amount of material or products measured at a point in time. Finally, flows are specified. These flows indicate the transport of material between processes, or coming into the system or going outside the system boundaries. Most raw materials used in construction require processing in order to be used by industry (e.g. steel requires iron ore, coking coal, aggregates and additives). The common construction materials used in house construction are presented in Table 4.

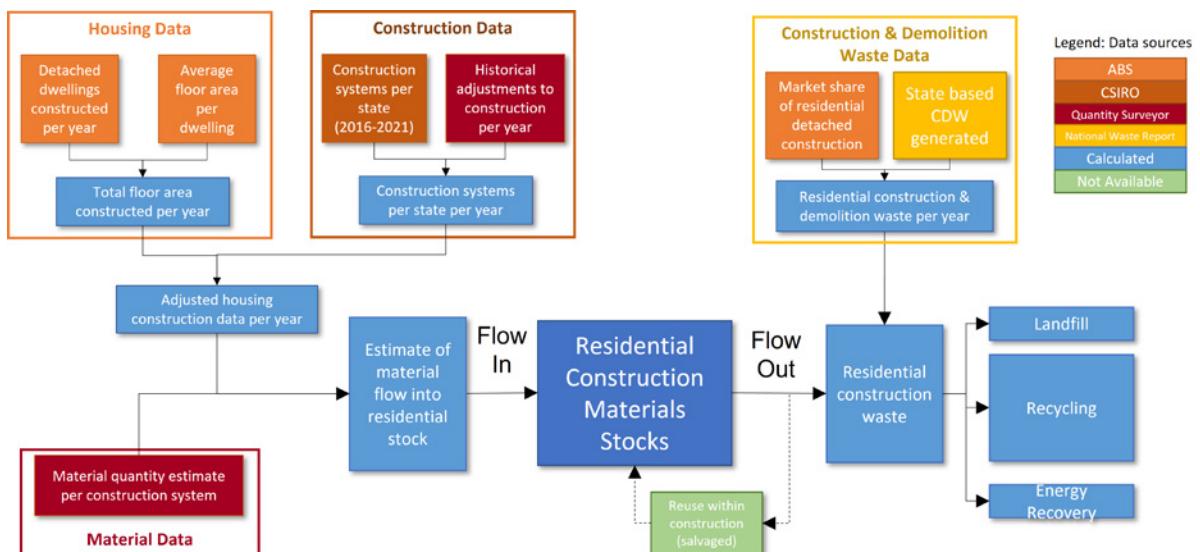
Table 4: Common construction materials

Non-organic materials		Organic materials
Mineral-based	Metallic-based	
• stone	• steel	• timber
• bricks	• aluminium	• bitumen
• glass	• copper	• plastics/ synthetics
• cement	• zinc	
• concrete	• cast iron, etc.	
• mortar		
• earth		

Source: Wendehorst (2011: 3)

Typically, MFAs are static, which means they are calculated at one point in time. However, by combining the top-down and bottom-up approaches, the research team went beyond the static nature of an MFA to produce a dynamic simulation and model. They did this by extending the analysis so that it took account of changes in the design and construction of houses over time, and developing a database incorporating bottom-up field research data. The data were generated from interviews (see Table 6) of a senior quantity surveyor, other construction industry professionals, and researchers who understood the main historical changes in house design and construction. This bottom-up data on the changing material composition of typical houses over time was integrated with state-specific housing-completion data to get state-aggregate top-down analyses of stocks and flow for houses. A list of the databases used are presented in Table 5. The assumption that the average house lasts for 60 years underpinned the calculation of the material stock for all houses in the Australian housing system. Figure 2 presents a map of the mixed-methods data collection developed for this research.

Figure 2: Summary map of mixed-methods data collection for modelling residential houses material flows



Source: Authors

Table 5: Data/assumptions and sources used in the MFA model

Data/assumptions	Source
Construction work done: residential detached	ABS (2022b), 8752.0 Building Activity: Table 39 Number of dwelling unit completions by sector, states and territories: original
Residential floor area	ABS (2022b), 8752.0 Building Activity: Average Floor Area NHFIC (2020), State of the Nation's Housing 2020
Construction systems	CSIRO (2022) Australian Housing Data Portal
Material requirements per construction typology	Quantity surveyor periodised analysis of material use in residential housing
Estimate on double-storey construction	Houghton (2021) Usage in Residential construction 2017–18 dataset: Report on methodology and results, FWPA
Share of construction market that is residential housing	ABS (2022b), 8752.0 Building Activity: Table 10. 'Value of building work done, states and territories—chain volume measures'
Share of residential housing that is detached houses	ABS (2022b), 8752.0 Building Activity: Table 39 'Number of dwelling unit completions by sector, states and territories: original'
Steel and timber framing market shares	Australian Construction Insights (2018), <i>Framing material use in residential construction</i>
Construction and demolition waste generated	Pickin, Wardle et al. (2020), National Waste Report 2020
Breakdown of source of construction waste	Crowther, P. (2000,) 'Building deconstruction in Australia', in <i>Overview of deconstruction in selected countries</i> , CIB report no. 252
Material Industry Data	IBIS World (2022) Industry Research Reports: C2031 Cement and lime manufacturing in Australia C2033 Ready-mixed concrete manufacturing in Australia C2021 Clay brick manufacturing in Australia C1492 Wooden structural component manufacturing in Australia E3223 Roofing services in Australia

Source: Authors

Table 6: Interviews conducted for the material flow analysis

Participants	Industry	Number of interviews
Participant 1	Quantity surveyor	5
Participant 2	Steel research	1
Participant 3	Timber institute	1
Participant 4	Research institute	2
Participant 5	Landfill	1
Participant 6	Steel	1
Participant 7	Brick recyclers	2

Source: Authors

Limitations and exclusions were set during the research so that research results were achieved in the time frame required. This MFA analysis is a first for Australian housing research. It has been undertaken in a context where very little research and policy attention has been given to the materiality of the housing stock. This gap contrasts with what happens in many other developed countries. For example, in the UK there is a long history of surveying housing stock and the condition of the stock (Department of Communities and Local Government 2017).

The main limitations of this research are areas where the MFA could be further extended to improve the outcomes of the study. The principal limitations of the MFA are outlined below.

- It is limited to detached housing construction, and did not include multi-unit apartments and townhouses, which limited the complexity of the construction typologies and data collection required for analysis.
- The modelling does not include illegal dwellings and residential alterations and additions. Measured in terms of gross fixed capital formation, housing alterations and additions are almost as significant as new housing (Dalton, Hurley et al. 2013).
- It only considers the main structural elements of the house: walls, floor structure, roof and windows. Furnishings, fit-out of bathrooms and kitchens, wall and floor coverings and landscaping requirements are all excluded from this research.

1.4.2 Industry-leading case-study analysis

Qualitative research was used to explore material circularity in two industry-leading case studies. First, a list of potential case studies was identified through a search of the grey literature for projects built within the last four years. Keywords used in this search included 'materials', 'circular economy', 'built environment', 'sustainable', and 'award winning'. The keywords were selected on the assumption that use of these words might demonstrate some application of CE principles. Eighty-two projects, both high-density and low-density, were identified this way, and they were examined for evidence of the application of CE principles and sustainability excellence (e.g. awards, high-star ratings). Projects that demonstrated good or excellent sustainability design but no evidence of CE thinking were deleted.

This left six potential projects, five of which were low-density housing, and one was high-density (Nightingale Village). Of the five low-density projects, two were outside the state of Victoria, and were inaccessible due to COVID travel restrictions; they were deleted. The three remaining low-density projects were assessed again for evidence of the application of CE thinking in their design and construction. The Cape was ranked first. The project managers of The Cape and the Nightingale Village agreed to participate, and were confirmed as the low-density and multi-unit project case studies for the research.

The primary research method was semi-structured interviewing of project directors, architects, project managers and consumers (see Appendix 2). A total of 13 interviews were conducted, six from The Cape and seven from Nightingale Village. These interviews were supplemented with site visits, photographs and document analysis. These visits provided a clearer idea of context and offered an opportunity to ask further questions. The interviews were conducted online in mid to late 2021, using Microsoft Teams due to COVID-19 restrictions. Site visits followed in early 2022.

The interviews were transcribed, then analysed using NVivo 12. Initial codes were chosen as the researchers became familiar with the projects and the CE literature. They included 'building materials', 'cost', 'design', 'building performance', 'social sustainability', 'vehicles', 'end-of-life', 'drivers', 'challenges', 'affordability' and 'consumer collaboration'. The initial codes were reviewed by another member of the research team for relevance to building materials and material circularity. Codes, such as 'social sustainability' and 'vehicles', with little relevance to material circularity, were removed from the second-stage analysis.

The second stage of analysis was guided by drawing on the analytical framework created by Potting, Hekkert et al. (2017). The initial codes from the first stage of coding were analysed, including 'building materials' and 'end-of-life'. This identified and categorised examples of CE thinking, including reuse, repurpose, rethink, reduce and recycle. These categories were reviewed and agreed by two members of the research team.

1.4.3 Supply-chain materials analysis

Three case-study materials, concrete, steel and timber, were chosen for the analysis of the way institutions shape the flow of building materials into and out of residential housing in-use stocks. A starting point for each building-material case study was recognising that each of these materials is manufactured by companies that pursue what Fleming, Merrett et al. (2004) described as the 'economics of strategy'. A set of headings used to guide the research included financing, insurance, standard setting, and regulation, designing and specifying, technological innovation, upstream and downstream supply chain capacities and built-environment governance.

The first step was to map the supply chains for concrete, steel and timber using IBIS industry reports. These reports present industry analyses on market characteristics, operating conditions, performance, forecasts and major industry participants. Mapping the supply chains started with identifying the industries that directly supplied housing industry builders with concrete, steel and timber products and associated services. These immediate suppliers formed Tier 1, which in turn are connected back to Tier 2 suppliers, and so on to subsequent tiers. These reports were used to develop maps of the three industry supply chains that supply builders (see Section 4).

The second step was to conduct 20 semi-structured interviews (see Table 7). Questions were prepared for each interview, usually with five to seven questions, and sent to the participants a few days ahead of the interview (see Appendix 2). The interviews lasted between 60 and 120 minutes, sometimes taking two sessions. The interviews were transcribed and analysed using NVivo 12.

Table 7: Interviews conducted for supply-chain materials analysis

Industry	Participants interviewed and their role
Concrete (C)	Two participants: consultants
Steel (S)	Three participants: residential steel framer, steel manufacturers, industry association representatives, sustainability experts, data managers
Timber (T)	Ten participants: peak body representatives, engineers, developers, builders, economists, architects, sales manager, building managers
Plumbing (P)	One participant: industry association representative
Environmental certification (EC)	Four participants: not-for-profit organisation, federal/state government department officers

Source: Authors

Additionally, 15 participants contributed to an online practitioner workshop drawn from key actor groups in the building materials and residential housing sector. All participants were sent a briefing paper that provided the basis for the workshop, which focussed on priorities for CE materials supply, use, and end-of-use chains and mechanisms for change. A facilitator conducted the workshop by prompting and inviting participants to contribute, as well as recording responses to questions using an online whiteboard.

Together the mapping, literature review and interviewing provided sufficient data for developing and presenting an account of the institutional arrangements that shape the manufacture and use of concrete, steel and timber in the housing industry, including upcycling or downcycling of waste into secondary materials. This account of the institutional arrangements for the three industries is presented in Section 4.

2. Housing materials stocks and flows

- A novel stocks and flows analysis was created by recognising changing material composition of housing types over time, informed by ‘bottom-up’ and ‘top-down’ methodologies.
- Modelling presents analyses of material flows within the residential housing system. However, these analyses and CE opportunities are constrained by current data systems.
- The data highlights the dominance and growth in the use of concrete within the housing system.
- The annual number of houses constructed has not changed significantly, although growth in house size and change in material composition has increased carbon intensity.
- Significant gaps in construction and demolition waste (CDW) data have been identified and must be addressed to inform the development of CE in the housing industry.
- Most construction waste is downcycled at a local or council level. Further analysis is required for local decision-makers.

2.1 Introduction

Improving understanding of material flow patterns is complex. For example, a multitude of different construction materials are interdependent, which means that some raw materials end up in a multitude of different construction products. At the same time, each construction material is part of its own supply chain or system. The life cycle stretches from raw material extraction and materials production, then to the consumption or construction phase, the material in-use phase, and all the way to disposal and recycling. Stock and flow modelling has been identified as a method to better understand the dynamics and behaviour pattern within the complex construction-material flow system.

The question addressed in this chapter is:

What is the in-use stocks and flow of building materials into and out of residential housing?

Here, ‘in-use stocks’ comprise our existing housing stock, a materials assemblage of embodied energy and materials. Understanding the in-use stocks of materials can support the planning and implementation of CE approaches to construction material—especially when focussing on capacity requirements. CE approaches can reduce the flow and impact of materials through long-lasting design, maintenance, repair, reuse, remanufacturing or repurposing, refurbishing and recycling. However, there is no assessment of the ‘in-use stocks’ of Australian housing and materials flowing in and out.

The complexity of the residential housing market, combined with limitations on data availability that became evident while developing the housing materials MFA model, necessitated the use of multiple assumptions. This was the primary reason for restricting the analysis to detached dwellings only. This is the area where data availability was the greatest. It was also the area where the knowledge of older professional practitioners was greatest. However, future research could use the same methodology and develop an MFA of ‘other residential housing’, which covers semi-detached, row or terrace houses, townhouses; apartments; and residential buildings not elsewhere classified. Similar to the work on detached dwellings, it would require the development of a typology of apartment types over time and a bottom-up analysis of their forms of construction and material use.

2.1.1 Material flow analysis

As outlined in Section 1, MFA can be used to assess flows and stocks of materials within a system defined in space and time. It is a methodology that connects the sources, pathways and intermediate and final sinks of a material. This is the context for growth in the use of MFA of construction materials and CDW:

- Huang, Shi et al. (2013) conducted an MFA for the built environment in China
- Hashimoto, Tanikawa et al (2007) focussed their efforts on Japan
- Condeixa, Haddad et al. (2017) investigated residential building stocks in Brazil
- Zhang, Hu et al. (2021) studied Dutch building stock.

An MFA for the residential built environment in Australia has so far not been carried out, although MFAs of individual materials have been undertaken (GBCA 2021; Pickin, Wardle et al. 2020). Stephan and Athanassiadis (2017) adopted a similar approach to this study by using a bottom-up approach to quantify the materials stocks of buildings in the City of Melbourne.

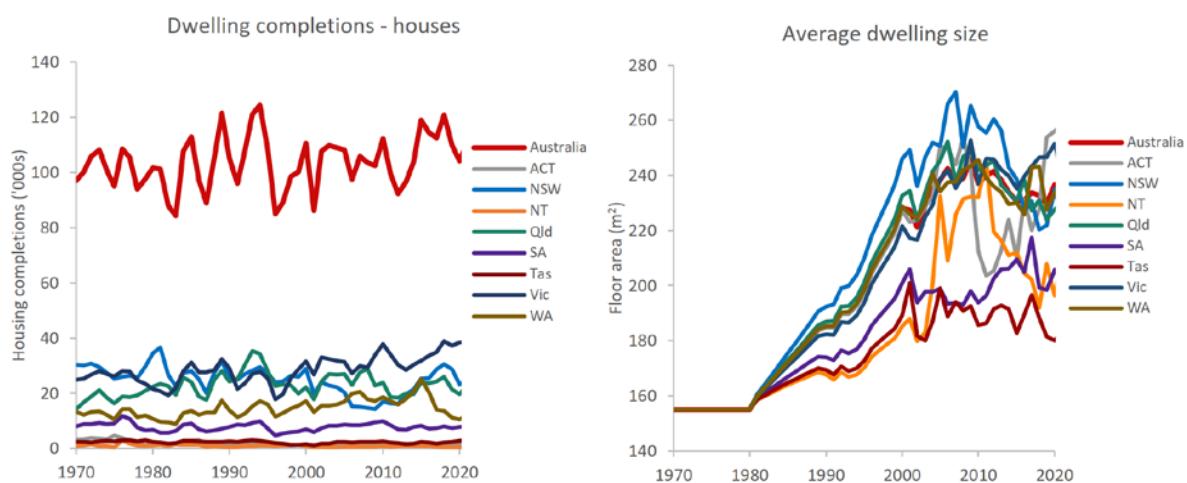
A consistent finding across these MFA investigations is that materials output from the economy is smaller than materials input to the economy, while the overall materials stock within the economy is growing (Bringezu and Moriguchi 2003; Brunner and Rechberger 2016). The difference between materials input and output is called net additions to stock (NAS) in the economy-wide MFA (Matthews, Amann et al. 2000), and is considered to be additional potential waste that will be generated in the future. Some MFA studies have also been extrapolated to consider the GHG impact of the materials used in the construction industry (Arehart, Pomponi et al. 2022; Stephan and Athanassiadis 2017).

In the housing industry, CDW has become a significant waste stream. In Australia, similar to many other countries, there are initiatives seeking to improve the rates of waste recycling. Due to its heavy weight, low unit economic value, and legislative and regulatory requirements, CDW is normally managed locally (Meglin, Kytzia et al. 2022; Wu et al. 2020). Therefore, the use of MFA requires close attention to the geographic scale of analysis so that waste management is governed across the local, regional and central levels.

2.1.2 Housing data

Housing industry data from the ABS presents the number of detached house completions per year, along with the average floor area over time (Figure 3). Over the 50-year period 1970–2020, the overall number of detached dwellings constructed in Australia has not changed dramatically, although there is periodic variation. However, there has been an increase in the size of houses being constructed. The data available since 1980 reveals an increase in dwelling size until the early 2000s, after which the size levelled out or decreased in some states. A breakdown of floor size by state was only available after 2005; prior to this, the variation between states was assumed to gradually decrease until they reached the same level as 1980.

Figure 3: Detached house completions and dwelling average floor area: all states



Sources: ABS (2021b) 8752.0 Building Activity: Table 39 'Number of dwelling unit completions by sector, states and territories: original'; ABS (2021b) 8752.0 Building Activity: Average Floor Area; NHFIC (2020).

2.1.3 Housing construction and material data

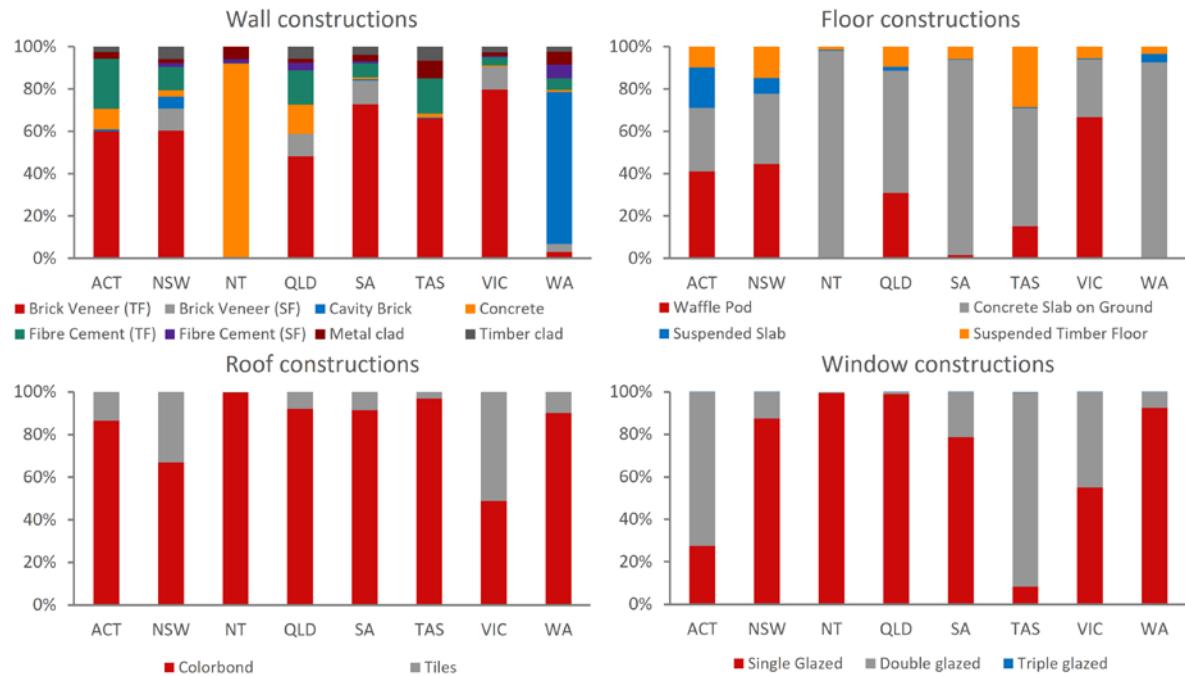
The CSIRO Housing Data Portal, based on data extracted from NatHERS certificates over the period 2016–2021, supports a broad analysis of the types of materials and products used in the construction of houses in all state and territories. Figure 4 presents a summary of the way materials are combined in the construction systems of roofs, walls and floors of dwellings. This figure shows similarities and differences across the states and territories. Some differences are associated with designing for different climates, such as the greater use of double-glazed windows in the cooler climates of Tasmania, the ACT and Victoria. Other differences are the result of different industry traditions and preferences across the jurisdictions, such as the almost exclusive use of double-brick construction in WA.

The CSIRO has identified a number of limitations of this dataset because of the design of the forms completed by energy assessors. Nationally, there are four NatHERS-accredited software tools used to assess residential energy efficiency and demonstrate compliance with the National Construction Code (NCC). Some of the limitations are outlined below.

- There are gaps in the required information, including requirements to indicate the frame material type and number of storeys in the house.
- There is uncertainty about the material and construction-system type because energy assessors can use whatever name they like to describe the construction system using a free text field. This leads to inaccuracies and a significant proportion of unknowns.
- The datasets do not include all new dwellings. The CSIRO estimates that 80 per cent of new residential buildings in Australia use NatHERS-accredited software as their means of demonstrating compliance with the NCC. However, further data from one of the accredited software tools is currently not captured by CSIRO and not included in the Housing Data Portal.

2. Housing materials stocks and flows

Figure 4: Construction systems for houses based on CSIRO Housing Data Portal: 2016–2021



Note: TF = Timber frame, SF = Steel frame

Source: CSIRO (2022), Australian Housing Data Portal.

While the CSIRO data provides a picture of contemporary house construction, estimates of the material stocks in use require historical data. This was developed through an analysis of the major changes in design and construction of houses in the period post–World War II. This analysis was used to adjust the assumptions and calculations of the material used in the construction systems, and then included in the MFA analysis to estimate material use in the housing construction system 1970–2020. A summary description of material use is presented in Table 8.

Table 8: Historical changes in house construction: 1950s–2020s

	Pre-1950s	1970s	1975	1985	2000–Now
Walls	Predominantly full brick in good areas, brick veneer in outer areas and fibro-clad in rural areas.	Mostly brick veneer and some fibro.	Change from asbestos fibro-cement clad to fibre-cement clad. Phasing out of hardwood framing, introduction of radiata pine framing.	Development of zicalume coating, introduction of lightweight steel framing and some replacing of timber framing. Introduction of double-glazed windows. Increase in proportion of two-storey homes.	
Floors	Everything built on a suspended timber floor.	Concrete slab on ground introduced and market grew quickly		Introduction of concrete efficient waffle pod slabs, with rapid market growth over the next 10 years.	
Roof	Previously terracotta tiles or corrugated metal sheeting. Cement tiles introduced from 1950s.			Introduction of Colorbond roofing.	Increase in use of Colorbond in market to modern-day dominance.

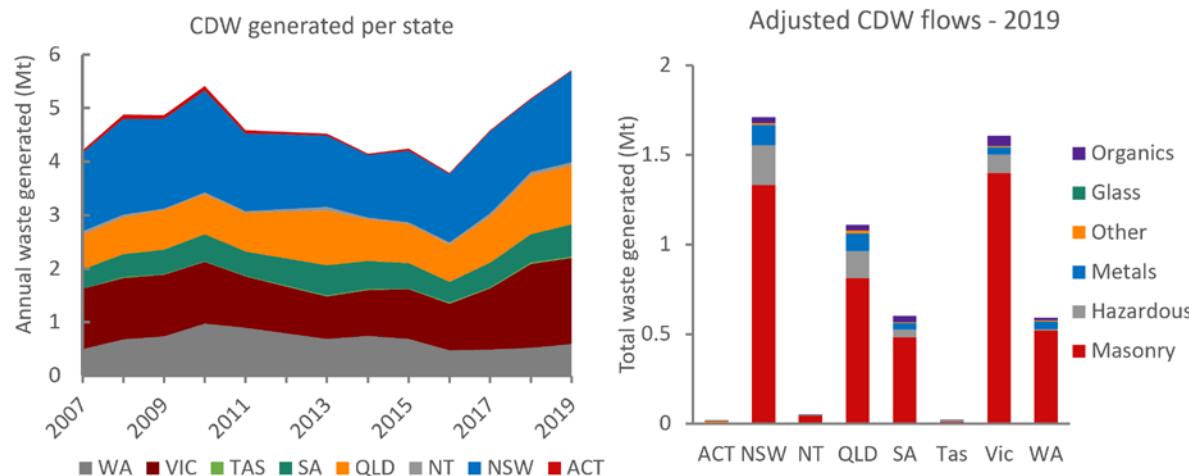
Source: Authors

2.1.4 Construction and demolition waste data

Nationwide construction and demolition waste data has been collected by each state and territory for the National Waste Policy Action Plan (2019). Sometimes this data is supplemented, manipulated or replaced by national industry data or estimates. Collection of the national waste data started in 2006/2007, however national data covering 2007/08, 2011/12 and 2012/13 was not collected. In this case, estimates have been made based on the trends in the data. Waste data is aggregated across all industry sectors—residential, commercial and infrastructure. No distinction is made between the source of waste—whether construction or demolition. For modelling purposes, the data available has been proportioned to the residential-detached sector based on the financial-market-share data available for both residential share of construction, and for detached dwellings share of residential construction.

CDW data for Australia is presented in Figure 5. It shows that waste flows are dominated by heavyweight materials such as masonry, which are largely recycled. Masonry includes asphalt, brick, concrete, plasterboard and rubble. Although there is some split treatment of these materials in some jurisdictions, these materials are typically disposed of together—and much of it ends up as rubble, which makes it difficult to determine the original quantities.

Figure 5: CDW generated annually by states and territories. Composition of CDW materials: 2019



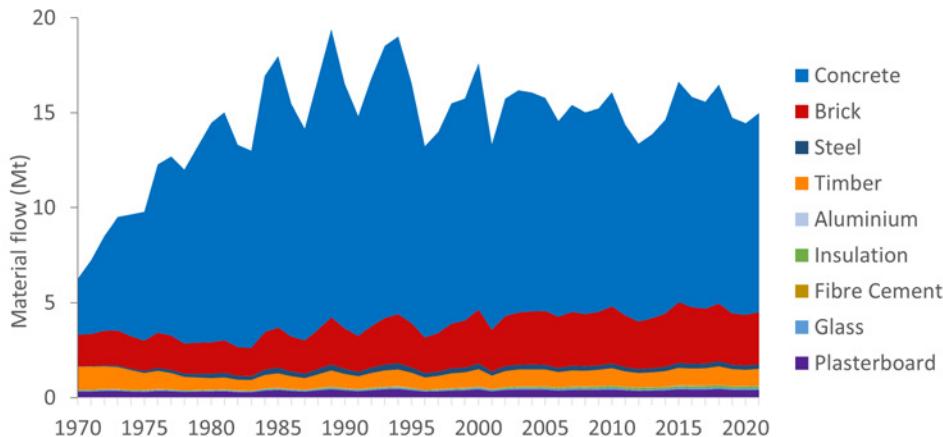
Source: Pickin, Wardle et al. (2020), adjusted by ABS (2022b) 8752.0 *Building Activity, Australia*, ‘Value of building work done, states and territories—chain volume measures and number of dwelling unit completions by sector, states and territories: original’.

2.2 Modelling results

2.2.1 Materials and embodied carbon flows

The housing construction assumptions in the MFA model are used to determine the flow of construction materials into the sector for the period 1970–2020 (see Figure 6). Variations in the flows are associated with the volatility of house completions data. The figure shows that these flows are increasingly dominated by concrete and brick, which together account for almost 90 per cent of the weight of construction materials after 1980.

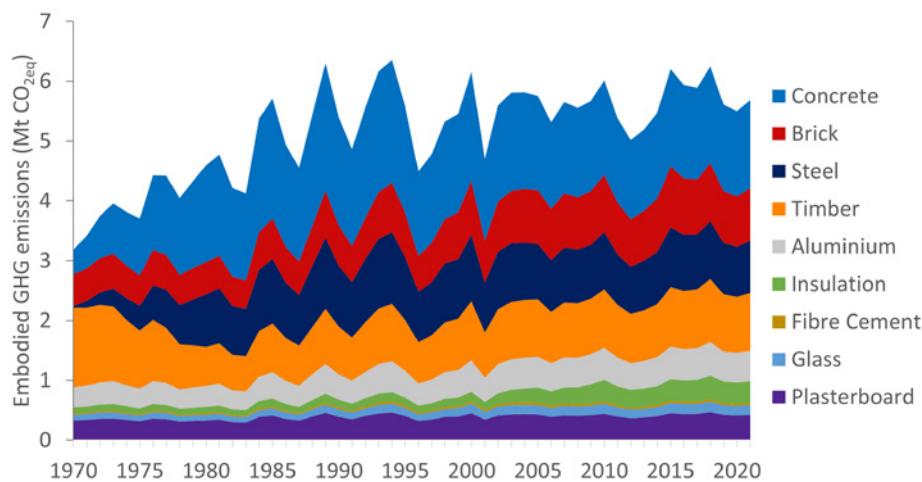
Figure 6: Annual estimate of material flow into residential detached construction: 1970–2020



Source: MFA model, primary and secondary data.

The material flows could be used to estimate the embodied GHG emissions resulting from materials flowing into the residential construction industry. This type of analysis would require additional knowledge of the materials used in construction and its life-cycle impacts. However, a simplified value can be assigned using material-embodied GHG coefficients from the Environmental Performance in Construction (EPIC) database (Crawford, Stephan et al. 2019). Results for the MFA embodied GHG emissions are given in Figure 7. This shows that over 50 years, the embodied GHG emissions in residential building materials have almost doubled from 3.2 million tonnes CO₂-eq in 1970 to 5.7 million tonnes CO₂-eq in 2020.

Figure 7: Estimated embodied carbon in the material stock: 1970–2020



Source: MFA model, primary and secondary data, coefficients from EPIC database (Crawford, Stephan et al. 2019).

In this study, multiple data sources with different time frames were combined in a spreadsheet-based MFA model, depicted in Figure 6. Housing data, including the number of houses constructed and average house size, is available for the past 50 years. Housing construction-material data is only available for the past five years. However, when this data is combined with historical assumptions, it is possible to estimate housing-material use over the past 50 years. With estimates of the material quantities in the housing construction, these datasets can be used to estimate the material flow into the residential-detached construction industry for the period 1970–2020.

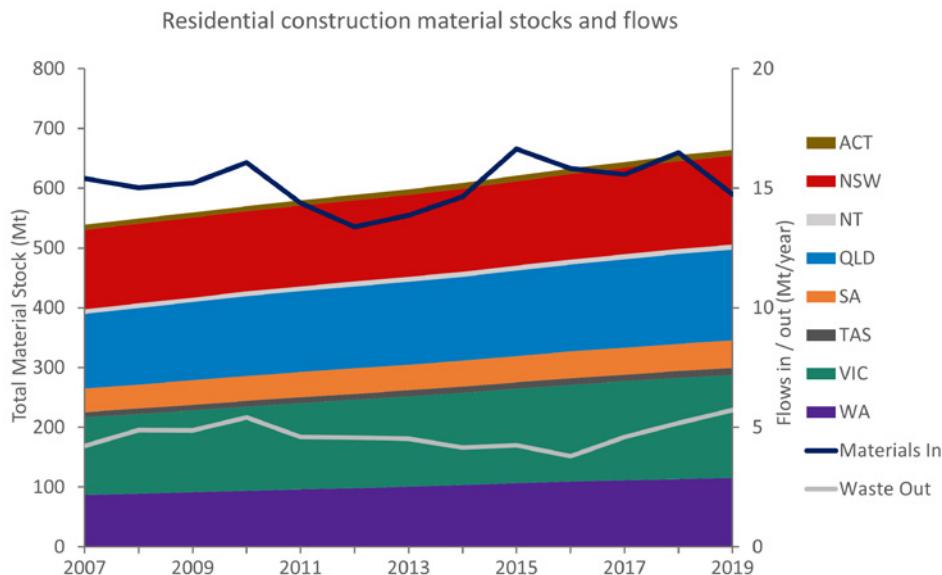
2.2.2 Stock and flow analysis

Material input flows are combined with the waste output flows to develop the overall stock and flow analysis (see Figure 8). Due to the limited waste data available, the stock and flow analysis is restricted to the period 2007–2019. Figure 8 indicates that new materials being used in construction are more than double the flow of waste out—which shows that the stocks in use of predominantly new or virgin materials are growing rapidly.

State-based and territory-based stock and flow analyses are shown in Figure 9, which show a similar trend, with increasing material stocks for New South Wales (NSW), Victoria, Queensland and Western Australia. The slight decrease in material flow for QLD and WA reflects the decrease in both floor area and the number of constructions over the period 2007–2019⁴.

New South Wales has a smaller gap between material flow in and waste out, resulting in a flatter increase in material stocks, whereas Victoria has a large difference between material flow in and waste out. This is reflected in the average waste to construction rate, which in 2019 was 0.27 tonnes per square metre of new construction for NSW, and 0.18 tonnes per square metre of new construction for Victoria. While this could be an indication of poor waste performance of NSW, the data available is not sufficiently reliable to draw conclusions.

Figure 8: Overall stocks and flows for residential construction: 2007–2019

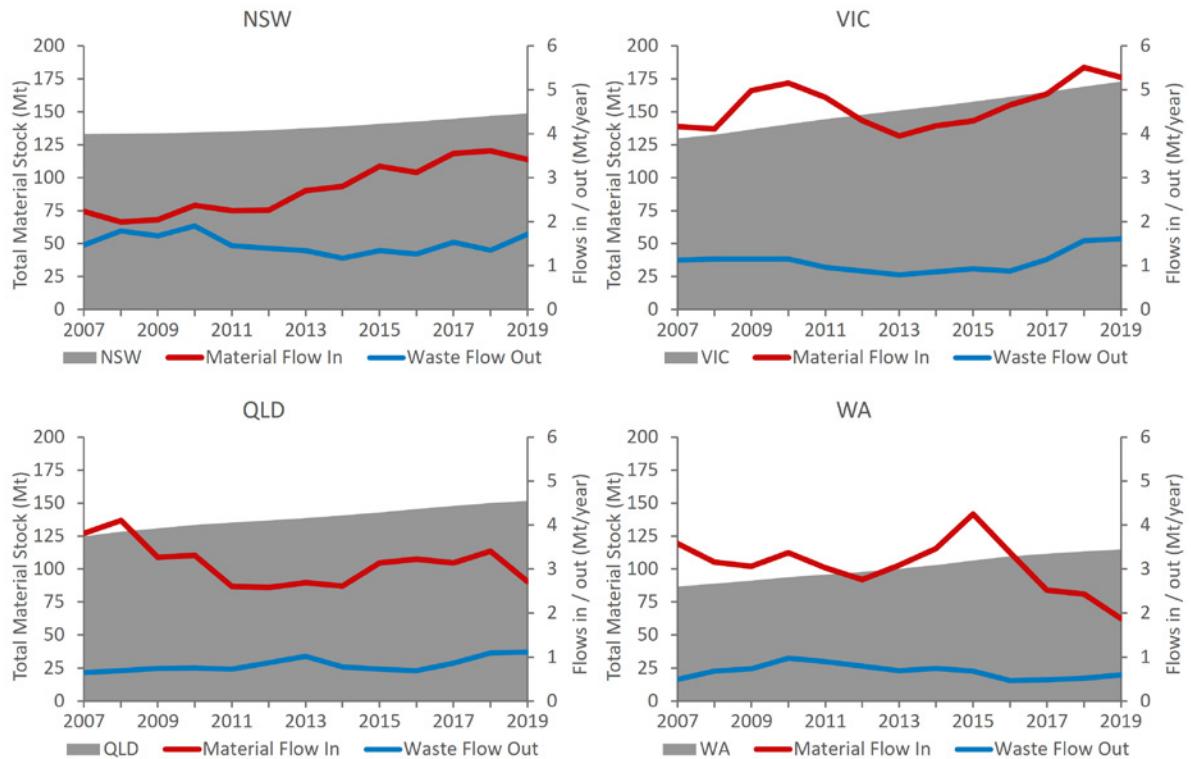


Source: MFA model, primary and secondary data.

⁴ We used a split-based approach of the market share of residential construction, assuming that waste is split proportionally, as this is all that can be done with the available data.

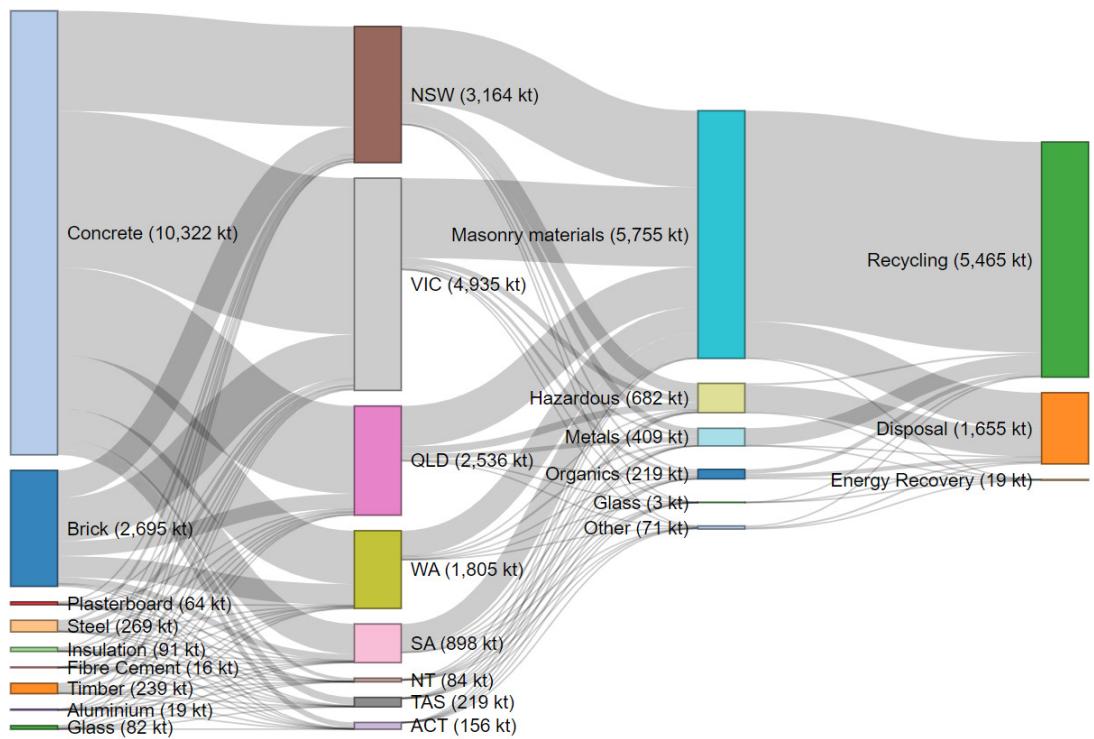
2. Housing materials stocks and flows

Figure 9: State-based stocks and flows for residential construction for NSW, Vic, QLD and WA: 2007–2019



Source: MFA model, primary and secondary data.

Figure 10: Material flow into and out of detached residential housing in Australia: 2019



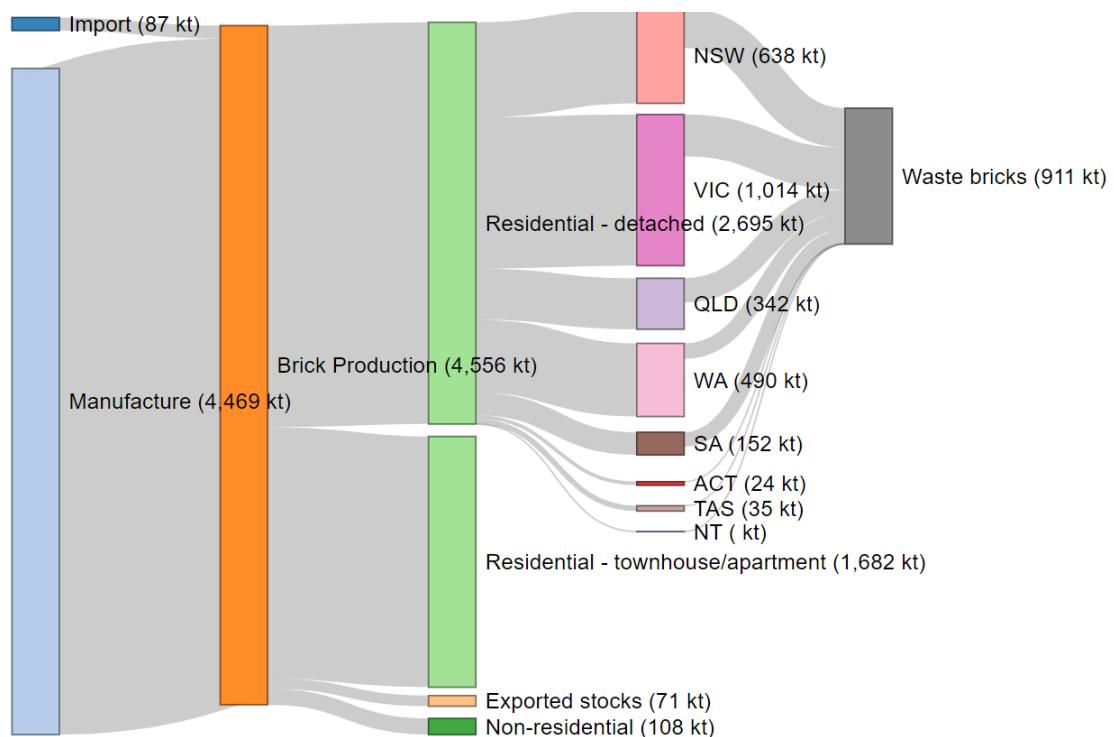
Source: MFA model, primary and secondary data.

The flow of construction and waste material in and out attributable to detached housing for each state and territory can also be visualised using a Sankey diagram⁵, presented in Figure 10. This diagram visualises the flow of waste materials from each state to recycling, disposal, and energy recovery.

2.2.3 Material investigations

Stock and flow Sankey diagrams are presented for the two major materials in use: concrete and brick (see Figure 11 and Figure 12). These figures are based on the modelling of available raw materials and import/export industry supply-chain data. Often only aggregate data on products was available. This does little to help CE thinking as it does not take into account product variations and end uses. The data presented in the figures is on an annual basis. However, it provides limited insights into the Australian industry for individual construction materials and their associated market application, particularly as aggregated data is often presented in financial terms rather than volumes. However, it is useful for identifying data gaps and visualising the material supply-chain context.

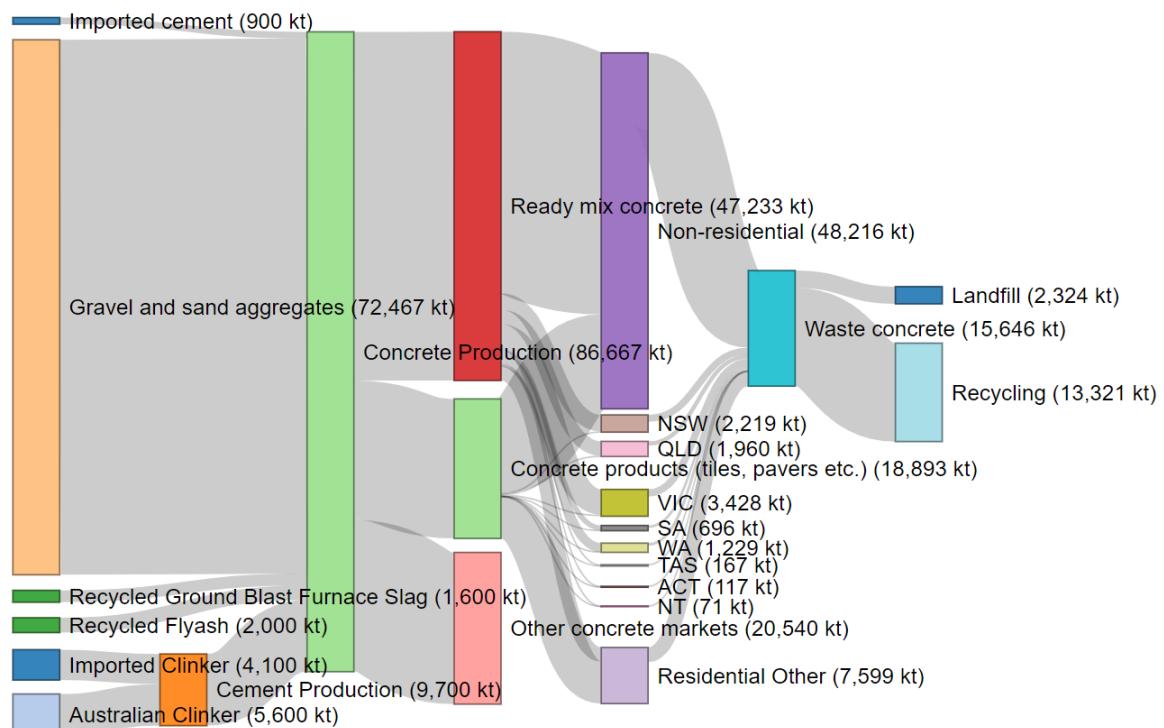
Figure 11: Brick manufacture, use and waste for detached residential housing in Australia using MFA analysis: 2019



Source: MFA model, primary and secondary data.

⁵ A Sankey diagram is a type of flow diagram in which the width of the arrows is proportional to the flow rate of the material. The Sankey diagrams presented in this report can be accessed interactively at <https://construction-analytics-uow.shinyapps.io/mfa-sankey/>.

Figure 12: Concrete manufacture, use and waste for detached residential housing in Australia using MFA analysis: 2019



Source: MFA model, primary and secondary data.

2.3 Data gaps and modelling limitations

During the course of the research, significant gaps in data were identified, which limited the accuracy and usefulness of the MFA modelling. These gaps were confirmed through interviews with building-industry stakeholders, and are summarised in Table 9.

While the data gives an overview of the material flow, it did not provide insights into material stocking points or inventory along the supply chain, and alternate reliable industry sources have not been identified. The stock and flow analysis diagrams, as presented, are of limited use for informing CE thinking and practice, as reuse of materials is not identified. There is a market for reuse of waste bricks—however, the size of the market is not known, and there is no data about brick reuse. In the case of concrete, and bricks that are not reused, waste is predominantly being downcycled into road base at a local level, or even landfilled. Hence, stock and flow analysis at a regional or state level would be more valid for understanding CDW flows.

Table 9: Identified data gaps

Data issue	Example or quote	Source
Salvaged materials and reuse of materials not captured	The salvaged-material market is growing, especially with a growth in environmental awareness. However, the market is not regulated and market participants are not required to report.	Participant 7
Compulsory data capture from the construction industry is inaccurate and incomplete	'A lot of documentation is handwritten information and hard to read and/or categorise. A large number of results end up in the "Other" category!' Number of storeys in a house and framing material is not recorded. Houses comprising mixed constructions (e.g. brick-veneer ground floor and fibro-clad top floor) can only be assigned to a single wall type, so only one material is chosen and the other data point is lost. Uncertainty around floor area of house used— inconsistency with ABS data.	Participant 4
Industries predominantly supply aggregated data, which provides little insight and end-use transparency	No information available for how much material is used in residential vs commercial construction. 'We have transparency into how much material we supply retail with, but where it goes from there—no idea.'	Participants 2, 3, 6
Inaccurate and incomplete waste data	Waste data is highly aggregated and not available at a regional (council) level. It has only been collected for the last 14 years, and not collected every year. There are inconsistencies in how states report data, and categorisation of waste into sub-types is not always available.	Participants 1, 5
Inconsistent data capture	Industry material data is often presented financial data, which does not easily translate to a volume. Material quantities used onsite are often not in an easy to use form (e.g. lineal metres of a wall, which does provide information about the material used; square metres of insulation which has a set thickness) and requires conversion and estimates. Window sizing is measured by window to wall ratio rather than absolute value.	Interviewee 1

Source: Authors

Historic data on the construction industry has been accessed from the ABS database to improve estimates of the current building stock. Data issues and gaps have been identified when determining the in-use stocks and flow of building materials into and out of residential housing. MFA is possible for construction material analysis at an aggregate level. However, little transparency is provided in terms of the application of that material and the predominant use. For example, the timber industry has overall volume data but would not be able to determine how much of that material is being supplied to the residential housing market (Interviewee 3). Many CE initiatives are regionally based, which means that aggregate state or nationwide data is less meaningful when informing localised circular problems or opportunities.

As part of the NatHERS certificate, builders are reporting to the Australian Housing Data Portal to determine energy efficiency ratings. The data provided is useful for MFA modelling. However, the data sheets provided by the construction industry are incomplete, and the accuracy of the data is not fully reflective of the actual build (see Table 9).

An additional data gap relates to salvaged and reused materials. Currently, no data is captured or made available on this particular niche or subsection of the construction industry. Finally, capturing sources of construction waste data is incomplete and inaccurate. Currently, available data sources cannot distinguish between demolition waste, construction waste and manufacturing waste.

2.4 Policy development implications for materials stocks and flows

There are large data gaps that challenge researchers who are seeking to identify and quantify the stocks in use in the residential housing sector. Further, the databases containing relevant data are not connected. Addressing data gaps by identifying new data sources and expanding available data that can be used by decision-makers at local, regional, state, territory and national levels is essential for the development of a CE within the housing system.

It is estimated that concrete and bricks constitute the largest flows of high-carbon construction waste going into and coming out of the housing system. Currently this type of CDW is being downcycled and used to supplement regional road and railway line infrastructure projects (e.g. roads and railway line ballast). It is unlikely that a high-value reuse strategy for concrete and bricks, similar to the scrap steel industry, will develop. It is important that data that can be used to make decisions about the best reuse of these heavy carbon-intensive materials is made available for local and regional decision-making.

Closing data gaps

In order to achieve impact in practice, database development is required that captures the material composition of buildings long-term through the use of ABD and material passports; this would allow information flows along the supply chain and support better coordination of supply and demand of materials. Also, data on the flow of reuse of salvage of materials must be captured so that the nature and extent of circularity is monitored.

Improving data relevance

The research revealed that the housing industry is a fragmented industry. For example, Western Australia continues to largely build houses using double brick, whereas brick veneer is the norm in NSW and Victoria. Also, there are big differences between urban and regional Australia in the use of cladding materials. Data series should be developed so that they can be used to reveal the geography of material use in residential housing design and construction.

Improving data accuracy

Data sources should be triangulated. ABS and CSIRO data provide a basis for top-down analyses of the materiality of the residential housing system. This data could be complemented by local council bottom-up data drawn from planning and building permit systems. Similarly CDW data could be drawn from local government landfill and demolition permit systems.

Accountability and accuracy

Higher accountability, responsibility and accuracy in the reporting to the CSIRO by the main contractor is required, so that more comprehensive and accurate data is available. Mandatory digitalisation of the residential construction industry, through the introduction of lodging of ABD and material passports, would allow for accurate representation of stock in-use and tracking of construction materials over the lifespan of the dwellings.

Regional and local data

Further, our research highlights the need for regional and local data. This data will enable local government to track material flows and CDW. This will inform the way they contribute to the development of local strategies for the reuse of CDW, as well as for the planning of future infrastructure projects and residential developments.

3. Sustainable housing and material circularity

- The Cape and Nightingale Village case studies considered material circularity against the background of measures that are already reducing operational energy and GHG emissions.
- Examples of circularity included reuse of brickwork, repurposing timber framing into furniture, recycling material offcuts and reducing the number of claddings on a building.
- On-the-job training was provided to the builders and subcontractors to produce houses that were efficient thermally by using thermal bridges and draught proofing.
- Challenges included financial costs for disassembly, material stockpiling restrictions and financial constraints.
- Future policy should consider mandates for embodied energy (EE) to be included in the building code.

3.1 Introduction

The question guiding this section is:

What supply-side drivers and dynamics can increase the contribution that building materials production and distribution can make to a CE?

Cape Paterson ecovillage ('The Cape') was conceived in the early 2000s, and in 2003 the developer purchased the greenfield land. The site is located on the outskirts of Cape Paterson, a rural town approximately 120 km south-east of Melbourne. After a lengthy process, planning approval was granted and construction started in 2013. Completion of The Cape is expected in 2024. It will contain around 230 detached homes, some short-stay accommodation dwellings, a conference centre, a community building/education centre and a community urban farm. The site is approximately 40 hectares, of which 50 per cent will be open space, and is being revegetated (The Cape 2021; The Cape Ecovillage 2020). The design and construction of houses follows design guideline requirements that go beyond minimum standards.

Purchasers work with the developer to produce a bespoke design for a detached house that meets design guidelines requirements and a NatHERS 8.5-star energy rating. In the main, these houses are sited on a concrete slab. However, there is considerable variation in the materials used for the building envelope. There are double-brick and brick-veneer walls, as well as walls clad in timber and manufactured lightweight claddings (Figure 13, right). Roof design and materials vary and include roof tiles and Colorbond metal. The walls and the roof spaces are insulated with high R-ratings materials and the windows are double-glazed.

The Park Life building (Figure 13, left) is one of six apartment buildings in the Nightingale Village (Nightingale Housing 2022b). The six neighbouring buildings were each designed by an award-winning architect using the guiding principles of the Nightingale Housing model (Nightingale Housing 2022a). The total site is approximately 4,500 square metres (Perinotto 2017), and will deliver around 200 apartments, which range from 27 to 42 apartments per building, and with seven to eight storeys in each (Nightingale Housing 2022a). There is also a range of non-residential space located across the lower levels of many of the buildings. The site is located 200 metres from the key activity centre of Sydney Road, Brunswick, five kilometres north of Melbourne's CBD, and 250 metres from the Anstey railway station.

The Park Life apartment building has seven stories and contains 37 apartments and two commercial spaces. Each apartment has an average 9+ stars NatHERS rating. The building has a reinforced concrete structure with loadbearing concrete wall panels and concrete floors. The windows are double-glazed and mounted in aluminium window frames. The stairwell running up through the building also facilitates airflow. The top floor is a common area that provides residents with a common laundry, an amphitheatre, and an area for growing food. Specific sustainability features include: all electric, no gas; an embedded electricity network supplying 100 per cent GreenPower; rainwater collected for common-area use and commercial tenancy toilets; reticulated hot water heat pump system; secure bicycle parking, close to public transport and easy access to 10+ car-share vehicles.

Figure 13: Nightingale Village (left) and The Cape (right) construction sites: January 2022



Source: Photographs by the authors, 2022.

In Australia, the key principles underpinning a CE are often referred to as the '3Rs': reduce, reuse, and recycle. Potting, Hekkert et al. (2017) extend these by setting out 10 strategies for a CE. The first and most important strategies relate to smarter manufacturing and product use. These are to:

- refuse products—such as avoiding plastic packaging
- rethink—through intensive product use, product-sharing or multi-functional products
- reduce—by increasing manufacturing efficiency and using fewer natural resources and materials.

Second, there are strategies that extend the lifespan of products and parts in both new and existing buildings. These include:

- reuse products in good condition and fulfilling their original function
- repair and maintain products
- refurbish by repairing and updating old products
- remanufacture by reusing product parts in new products
- repurpose by using a product, or product parts, in new products.

Third, there are two least preferred CE strategies that focus on the use of waste. They are:

- recycle by reprocessing materials to the same or lower-grade quality
- recover energy by incinerating materials.

Within the building sector, recycling is more common than reuse, although the potential economic and environmental benefits of reuse are believed to be significantly greater (Eberhardt, Birgisdóttir et al. 2019).

3.2 The Cape: Cape Paterson, Victoria

At The Cape, there was an emphasis on minimising material where possible, as well as selecting products that were more natural and less manufactured:

[We are] trying to minimise the amount of products we're using ... So with a lot of our homes, we try and stick to a minimum two claddings rather than having a whole bunch of different products; and [we] particularly tried to steer away from a lot of manufactured products ... and try to stick with more natural products. (design and build manager)

This reduction of material meant less to recycle at the end of the lifespan. It also helped with reducing waste through reusing leftover material for other homes:

The effect of using less materials in the home reduces that [waste] significantly ... So you might see homes that have five or six different claddings on them, there's going to be a lot of offcut from all those different products. Whereas if you've just got timber and say, a metal cladding, you've got much less offcuts of those; and you can get your quantities right much easier and not have to buy as much product. So that's definitely a really important factor in doing that. But also, by keeping a similar tone throughout homes and steering our clients towards similar products, we can reuse any leftover material from one job to another. So that certainly helps reduce any waste as well. (design and build manager)

Future disassembly and reuse was also considered:

If we do have to do a demolition, we're trying to separate all the metals, separate bricks, things like that, and send them off to a better home to be reused, if they can't be reused on the home itself. (design and build manager)

Brickwork was a common example of where this had occurred:

The internal thermal-mass walls are all recycled beautiful red brick. So that would just be a matter of pulling apart the build and repurposing the material. (developer)

Other materials were more challenging to reuse, but still possible. For example, timber members in the wall linings would not be reused to structurally support a house in their next life, but could be repurposed to have another function, such as furniture:

One thing we steer away from a little bit in terms of any [wall] linings and things like that is reuse of timber, because it's more from the warranty perspective, because once you take it out of the environment it's currently in and put it in a new one it can warp, twist and change. So, we generally try and steer clients towards maybe getting a furniture piece made or something like that from those materials. (design and build manager)

Material selection and choices were made with consideration for the end-of-life:

We use corrugated claddings all the time, we know that they can be recycled being a metal cladding; and then timber claddings, something that we use predominantly in our homes as well, is a product that can be reused or repurposed down the track. (design and build manager)

This included many materials within the home, such as the kitchen benchtops:

Looking at different types of stones; so rather than the standard, reconstituted stones, we are looking at products like recycled glass, and other recycled products as part of their benchtops as well. (design and build manager)

This includes materials used around the homes, such as recycled concrete for footpaths:

We strongly encouraged low-grade alternatives, low-grade concrete. We use recycled materials in our road base, in our concrete, for footpaths and that sort of stuff. (development manager)

To assist in achieving circularity goals, there was preference for manufacturers and installers who considered recycling. For example, plaster installers would recycle waste:

As the plaster is going on the walls, behind me here, we'll probably have five or six sheets that have cuts and things left over. And the [plaster installers] actually have got a recycling system as part of their product as well. So, they'll come in and take any leftovers away and recycle. (design and build manager)

There were financial challenges with delivering circularity across the dwelling life cycle. Increased building costs had reduced choice in material selections:

And the other thing is that that's because building costs are expensive at the moment, that drives some of the material selection that we can use. (building designer)

At the end-of-life, there is also a lack of economic incentive to disassemble and reuse or repurpose materials:

It's actually cheaper and easier for a builder to come in and just grab the house and throw it in the tip. Basically, instead of someone coming by and then pulling it apart, you know, stick by stick, and recovering stuff. So, you know, the economics of recycling old homes doesn't stack up financially. (building designer)

As well as financial cost concerns, there were also challenges with building code compliance for new, innovative and sustainable products:

For manufacturers who are trying to manufacture more sustainable products, it can be really hard to get those tried, tested, approved [and] into homes and complying with the NCC. So, I think that's been a challenge, because the NCC hasn't had a focus, or not enough focus, on sustainability aspects of the build, as well as giving a bit more freedom to push that bar. (design and build manager)

While there were many examples of circular thinking with building materials, there was also an admission that the main priority was operational energy:

Look, there is consideration to the whole life cycle, and there is consideration to embodied energy and the sustainability of virgin material, and that is discussed in the guidelines. But I think it's fair to say that our priority is on the operational energy use. (development manager)

This was highlighted through the striving for minimum star ratings across The Cape:

So the driver was to comfortably achieve the minimum standards that we set in the design guidelines, which was 7.5-star energy-efficient, all electric fit-out. (developer)

To help achieve this they were required to educate and challenge the builders to work differently from normal:

We take them over, like thermal bridging, and how important it is to, to try and stop these breaks. And just to do a few other things that they normally wouldn't do, like we showed them how to seal the house right up on the external junctions of a timber frame; we get them to put under-slab insulation in there while they're building, so that we stopped that thermal bridging; we batten out a lot of the materials so that we have that air gap outside; and, obviously, sealing up windows and doors, and things like that. (building designer)

3.3 Nightingale Village: Brunswick, Victoria

At Nightingale, there was an approach that focussed on material reduction:

There was an ethic about don't stick anything on that doesn't need to be there, every surface should be integral. You know, if you shake it and it falls off, it shouldn't be on the building in the first place. (urban designer)

This approach went against beliefs about what 'the market' wanted:

That's the great lesson of The Commons and Nightingale—how much you could avoid unnecessary claddings and finishes that are added to buildings because we think that's what the market wants ... we can strip that out. So, there's certainly an embodied energy component to the removal of aluminium panel, minimisation of plasterboard, and others. (urban designer)

Architecturally, the minimalist design acted as scaffold for residents' possessions to become the architecture:

There was an idea that instead of lavishing the facades with ... 'architecture', it was better to create a scaffold for people's lives that would allow their possessions to become the architecture. (urban designer)

3. Sustainable housing and material circularity

There were some examples of recycled materials, such as recycled brickwork in landscaping areas and timber flooring, but this was not delivered at scale:

[Nightingale Skyhouse] has a recycled timber floor. So that is a hardwood. It's a 20-millimetre product, it was recycled before it came to our building. And it's old-style top-nailed, can be removed and reused elsewhere, as it was before it came to this site. And you know, we love doing that. But that's, that's unique to that building because it becomes pretty tricky to deliver that at this scale, actually, to do with supply chain, there's not that much recycled timber flooring out there since we did it. (architecture and sustainability director)

Though there were challenges preventing more widespread reuse of materials, such as cost and storage:

One of the big barriers to material reuse onsite, even for Nightingale, is logistics and storage. So Nightingale sells their bricks to a yard and Kensington [Assemble Housing] buys them back from somewhere else because they can't pay the cost of rent during that time. (urban designer)

There was also an acknowledgment that materials were not particularly selected for their ability to be reused or repurposed at the end-of-life:

I wouldn't say there is a material in there that is specifically innovative when it comes to circular economy by intent. I think it's a timing thing, right? Like, if you look at European Commission, circular economy sort of guidelines that were being written in 2014, people have only just started talking about them in Australia in about the last three years. So it's sort of, I think, at the time, it wasn't something that was as high priority, I was certainly familiar at the time with design for disassembly as a principal. (urban designer)

Between buildings, there was also a focus on material reduction:

There's kind of not a lot of materials in between spaces. It's kind of pretty much the rule buildings. We've got no ceilings, and we just got the pavers. So from my building, no, I don't know anyone else's intimately. But no, I suppose it's almost like, return back to that idea of being [reductionist] rather than recycled. (architect)

One of the main drivers for the reductionist approach was financial cost:

I would actually say that the buildings have become much more bare bones through the process, largely because of cost. But I think that was our ambition at the start, anyway, was not to be too lavish. (urban designer)

Being innovative with material choices was also challenging within the medium-residential space, as builders would price-penalty materials that they viewed as risky:

I think this is where the rubber hits the road with the problem with circular economy principles. We are all price-takers in designing construct contracts with builders. So, Nightingale can have any aspiration it wants, but whoever is building the building, they will name a price, they will name the terms, and they'll price the risk. And as long as a builder sees certain materials systems as risky, they are just going to put a relatively arbitrary price on that as a penalty. Because of the nature of you know ... you could call it economic theory, you could call it a cartel effect of the building industries. Having this command, particularly of materials such as precast concrete, that really artificially penalises other materials that might be more suited to achieving the things we need. (urban designer)

The land value and scale meant medium-residential villages appeared to have greater challenges related to financial costs in obtaining the sustainable design they desired. This reduced material choices away from more sustainably desirable materials such as timber, and towards cost-effective materials such as concrete.

3.4 Assessment of findings against Rs framework

The central focus at The Cape and at the Nightingale Park Life apartment building was on energy efficiency and meeting a NatHERS star rating. While the reduction of embodied energy was not featured, there was still some consideration given to the reduction of materials, waste management, and the use of recycled materials. The designers of both case studies recognised issues that challenged movement towards circularity, specifically:

- the financial cost of planning for building disassembly at the end-of-life
- how costs restricted the choice of lower-carbon materials and alternative construction methods.

Nevertheless, initiatives had been made that could be recognised as CE measures and aligned with one of strategies in the framework created by Potting, Hekkert et al. (2017). The assessment of findings, using the Rs framework by Potting, Hekkert et al., is synthesised in Table 10.

Table 10: Synthesis of case-study findings using the Rs framework

R-framework	Explanation	Case-study example	Related case-study quote
R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product	Refusing materials delivered in plastic wrapping	'They reached out to a lot of suppliers and requested that things weren't plastic-wrapped.'
R1 Rethink	Make product use more intensive, by sharing a product	Contractors sharing equipment, plant and machinery during construction	'We'll grab one machine rather than needing to grab one each. So little things like that we're doing, just to work in together. Same as with temporary fencing.'
R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials	Reduce number of claddings	'We try and stick to minimum claddings.'
R3 Reuse	Reuse by another consumer of discarded product that is still in good condition and fulfils its original function	Reuse of brickwork	'So the bricks were salvaged, and they've been reused in building.'
R4 Repair	Repair and maintenance of a defective product so it can be used within its original function	Building materials are repaired and used. Also consideration of how to reduce future repair work.	'Instead of painting the concrete ... and then there's a maintenance issue ... we looked at putting a pigment through the concrete.'
R5 Refurbish	Restore an old product and bring it up to date	Materials restored and brought up to date	'There's nice, beautiful hardwoods in the ceiling ... when you pull this place apart, make sure that you recover all that.'
R6 Remanufacture	Use parts of discarded product in a new product with the same function	Timber used for furniture	'We generally try and steer clients towards maybe getting a furniture piece made or something like that from those materials.'
R7 Repurpose	Use parts of a discarded product or its parts in a new product with a different function	Brickwork used for landscaping	'There's definitely some recycled bricks in some of the landscaping areas.'
R8 Recycle	Process materials to obtain the same (high-grade) or lower (low-grade) quality	Using recycled materials in road base	'We use recycled materials in our road base.'
R9 Recover	Incineration of material with energy recovery	Timber is burned for energy	'I will probably churn it up and use it for firewood.'

Source: Authors, participants.

3.5 Policy development implications for circularity approaches

The material strategies in both case studies had different circularity approaches. The Park Life Nightingale Village case study focussed more on reduction, while The Cape appeared to focus more on strategies that included materials reduction, but also refuse, reuse, rethink and repurpose.

Energy efficiency is mandated within the NCC, but as yet there are no requirements to measure and reduce the carbon footprint of buildings. Policies that could contribute to reducing embodied energy include the following.

Incentivising disassembly

The findings revealed that it was difficult for developers and builders to justify the costs of disassembly of existing buildings as the cost of disposing of materials in landfill is less. There is an opportunity for policy to encourage disassembly and material reuse by linking these practices to a broader reduction strategy, which would reduce built-environment embodied carbon.

Facilitating practical disassembly challenges

Regulations on recycling and reuse, such as 'Recycled First' in Victoria, tend to focus on the 'end-of-pipe solutions' as a means for encouraging CE. They do not embrace the higher-order R-principles, such as reuse, rethink, repurpose or remanufacture. For example, regulations could support the stockpiling of disassembled construction materials suitable for reuse.

Changing work practices through training for energy efficiency and CE

Contractors at The Cape were educated and challenged to change their work practices to build more energy-efficient buildings, and to test for energy efficiency by blower door testing⁶ the houses upon completion.

⁶ Blower door testing is a method to verify air tightness in construction, which quantifies the amount of air leakage.

4. Material supply chains and actors

- The concrete and steel industries have committed globally and nationally to emission-reduction ‘pathways’, and are developing decarbonisation strategies.
- Timber is a biomaterial and a means for lowering embodied carbon in housing. But timber use remains limited in Australia, particularly in the multi-unit apartment industry.
- Builders source materials from suppliers with little or no assessment of the embodied carbon levels created during the manufacture of those materials and their journey along industry supply chains.
- Education and training systems could increase understanding by housing industry participants of embodied carbon in building materials.

4.1 Introduction

Housing industry builders draw materials for house and multi-unit apartment construction from many supply chains. They can be mapped using the IBISWorld Industry Research Reports, starting with the HCl and MUATCI sectors within the ANZSIC Construction Division (Kelly 2022b, 2022a). Because residential building projects are time-limited, one-off projects, these supply chains are being continuously dismantled and remade. Our mapping established that 27 industries deliver products and services to a residential building site where a house or apartment building is being constructed (see Appendix 4).

The question addressed in Section 4 is:

What are the prospects for reforming material supply chains so that they increase their capacity to contribute to a CE?

To answer this question, we examined three case-study building materials: concrete, steel and timber. These materials have been layered into the housing stock over many years, and continue to be used in construction by the HCl and MUATCI builders to build new housing and to retrofit and maintain existing stock.

Each material was examined by focussing on four themes:

1. **Embodied carbon:** carbon emissions associated with the provision of raw materials, materials manufacture and use in building construction—including transport.
2. **Industry structure:** industries have distinctive features and characters evident in the size of businesses, capital intensity of businesses, competition and geography.
3. **Innovation:** change in business practices, processes, techniques, products and services brought about by using knowledge and skills.
4. **Industry challenges:** substantive issues require innovation and technical change, along with institutional change in pursuit of decarbonisation.

These materials were chosen as case studies for three reasons. First, 'globally, cement and steel are two of the most important sources of material-related emissions in construction' (Adams, Burrows et al. 2019: 24) and 'reinforced concrete and steel frames underpin most of today's global buildings construction' (IEA 2019: 54).

Second, phasing out the use of these materials is not a realistic option, given the habitus of centuries of concrete and steel use. Instead, decarbonisation of material production and smarter material use and reuse has become the focus.

Third, timber can be used as a structural material and, at least in part, could replace the use of concrete and steel. Some argue that growing trees sequesters atmospheric CO₂, which means that growing trees and using structural timber buildings can act as carbon sinks (Churkina, Organschi et al. 2020).

Embodied-energy (EE) intensity, which is the combination of material quantity and EE coefficient of materials, is highly uneven across the housing system. According to Li, Foliente et al. (2021), housing typologies should be considered when analysing the life-cycle energy of residential buildings. Such analysis would typically include housing type, construction type and year. Materials are part of the equation as they have different EE levels and contribute differently to energy use, depending on building characteristics.

Six main materials contribute to residential EE: concrete, timber, brick, steel, plasterboard and carpet (Li, Foliente et al. 2021). The level of EE contribution is influenced by time, as the service life of some materials in older dwellings—such as carpet and plasterboard—is shorter than others in new housing, which results in higher recurrent energy. Housing type also matters, as apartment EE intensities are higher than houses by nearly 20 per cent. Timber has the lowest EE intensity of the three materials, whereas reinforced concrete has the highest (Li, Foliente et al. 2021). Less material is required for timber housing, whereas reinforced concrete apartments require large quantities of concrete and steel with high EE coefficients (Li, Foliente et al. 2021).

4.2 Concrete

Residential housing construction uses 30 per cent of Australian concrete (VDZ 2021: 9). However, the resulting carbon intensity of the two main housing types (HCl and MUATCI) is different. Apartments are 18 per cent more carbon-intensive than houses. This is because 'apartments are mainly constructed of concrete, whereas houses are typically built of brick veneer, timber, and double brick' (Li, Foliente et al. 2021: 8). Although there has been some decarbonisation of concrete in recent years—approximately 20 per cent—with further decarbonisation a prospect, there is a problem: overall, the carbon intensity of residential housing has been increasing.

The origin of this problem is found in urban and housing policies supporting the densification of suburban metropolitan capital cities, which result in an increase in the construction of new apartments. The successful implementation of this policy is evident in Figure 1, which shows the changing mix of new housing construction. The proportion of detached houses has decreased, while the proportion of apartments has increased. An unintended consequence of densification policy has been an increase in the carbon intensity of the Australian housing stock. This is likely to continue, perhaps mitigated by further decarbonisation of cement and concrete manufacture, design and use of lighter-weight concrete structures or use of alternative materials that are less carbon-intensive.

4.2.1 Carbon in concrete

In 2018, the cement industry produced about 7 per cent of global CO₂ emissions, and was the third-largest industrial energy consumer (IEA 2018). The industry has improved the energy efficiency of cement production and reduced its carbon emissions since 2009 (IEA 2018), and there are commitments from the cement industry at the global level to continue this improvement (GCCA 2021). However, the production and use of cement has been increasing and global cement consumption is projected to increase by 12–23 per cent by 2050. In Australia cement and lime industry production is one of the highest emitters of CO₂ (Kelly 2021a: 47).

Globally, the industry began planning for decarbonisation in 1999, when the World Business Council for Sustainable Development (WBCSD) commissioned a report *Toward a Sustainable Cement Industry* (Battelle Memorial Institute 2002). This led to the formation of the Cement Sustainability Initiative (CSI) and publication of the *Agenda for Action* (WBCSD 2003). In 2018, the CSI spun off from the WBCSD to become the Global Cement and Concrete Association (GCCA).

The GCCA is the principal association at the global level (GCCA 2021). It commits to percentage reductions in CO₂ emissions to be obtained across the manufacturing and use of cement and concrete. National industry associations are using the GCCA framework in country-specific decarbonisation roadmaps.

The NGO Beyond Zero Emissions (2017) was the first organisation in Australia to put cement GHG emissions on the agenda. Formal industry engagement with climate change followed when Cement Concrete and Aggregates Australia (CCAA) joined GCCA in late 2019. Industry leaders recognised that the industry was '*being left out of Australian conversations [about climate change], especially at a national level*' and that decarbonisation documents were '*appearing around the world*' (Participant C2).

Further, larger cement manufacturers were listed in the National Greenhouse and Energy Reporting (NGER) Scheme⁷ (Clean Energy Regulator 2022). Policy will be updated following the 2022 change of government through a commitment to require the Clean Energy Regulator 'to determine revised baselines for each facility in close consultation with industry' (Australian Labor Party 2021).

In 2020, industry leaders responded by commissioning an Australian decarbonisation pathways report that committed to net zero emissions by 2050, prepared by VDZ (2021). In the '*lead up to COP26*' it was conceived of as '*an outward-looking document [...] endorsed by the cement and concrete industry ... [as] previously you didn't have anything of that detail in the public domain*' (Participant C2).

Beyond the two lead industry associations, the Cement Industry Federation (CIF) and CCAA, contributions to cement decarbonisation through the supply chain are uneven. Larger manufacturers have developed some capacity. As Participant C2 notes, '*it's only really Boral, Holcim, Hanson, Adbri, and maybe one or two of the next level down [...] the big guys do that because they have the resources to be able to take part in this*'. Although there are signs that '*some larger Tier 2s are developing responses to both this [decarbonisation] and the market pull that has to happen to get this happening*'.

Decarbonisation is primarily a 'big guys' responsibility, as they produce lime which produces CO₂ emissions. Limestone (CaO₃) is the main ingredient, which is 'calcinated' in high-temperature rotary kilns to produce calcium oxide or lime (CaO) plus CO₂ emissions. This calcination process produces approximately 55 per cent of total cement and concrete CO₂ emissions in five integrated cement plants that supply 60 per cent of Australian cement. The other 40 per cent is manufactured from imported clinker and milled into cement.

⁷ The [National Greenhouse and Energy Reporting Act 2007](#) (NGER Act) is the national framework legislation for reporting and disseminating company information about greenhouse gas emissions, energy production, energy consumption and other information specified under NGER legislation.

Cement from both sources contributes the largest total of industry emissions. Participant C2 describes the concentration of embodied carbon created by calcination in cement manufacturing: '*Cement is about 12 per cent of the mass of a cubic metre of concrete, but it's actually about 88 per cent of the carbon load of a cubic metre of concrete.*' Another three types of emissions contribute to total emissions:

- 26 per cent are fuel-based emissions created through heating the kiln
- 12 per cent are indirect emissions from electrical energy usage
- 7 per cent are from transporting cement and concrete to the customer (VDZ 2021).

4.2.2 Concrete industry structure

Following significant industry restructuring, there has been a reduction of cement manufacturing plants from 13 in the late 1990s to five in 2022. These five plants are owned and operated by three industry groups. In 2018–19, these five plants produced 5.6 million tonnes of clinker. Also, lower-cost manufactured clinker is imported from Japan, Thailand, Indonesia, Malaysia and China. The volume of imported clinker has risen steadily, and in 2018–19 was 4.1 million tonnes. This clinker is manufactured into cement at 14 grinding plants owned by seven companies (VDZ 2021; Kelly 2021a).

The structure of the cement and lime manufacturing industry can be understood by focussing on three dimensions: concentration, vertical integration and capital intensity.

Industry concentration

Industry concentration in the cement and lime manufacturing industry is moderate (Kelly 2021). This is evident in the 39.4 per cent market share (MS) of industry revenue flowing to the three main manufacturing groups:

- Adbri (MS 19.4%)
- Cement Australia Holdings (MS 11.5%)
- Boral Limited (MS 8.5%).

These manufacturing groups also make the industry highly globalised, with approximately two-thirds of productive capacity in foreign ownership (Kelly 2020: 29). Smaller businesses largely focus on particular products, such as small-scale lime production, specialty cements and precast products, and often relate to regional markets or raw material quarries.

Vertical integration

Industry concentration is closely associated with vertical integration. It extends back to raw material supplies in the Tier 2 gravel and sand quarrying industry, where subsidiary companies of the three main groups have a 70 per cent market share medium-level concentration (see Figure 14). Similarly, manufacturers obtain materials from rock, limestone and the clay-mining industry, which has a 26 per cent MS concentration. Vertical integration also extends forward into the Tier 1 ready-mixed concrete manufacturing industry, which consists of approximately 1,500 geographically distributed batching plants. These plants prepare and transport aggregates to building and construction sites. This industry has a medium-level (66%) MS where four large vertically integrated multi-plant firms, which account for over two-thirds of annual industry revenue (Kelly 2021b: 9).

Concentration and vertical integration can create conditions for price-fixing and market sharing (ACCC 2022). But, at the same time, concentration and vertical integration also have the potential for developing and implementing decarbonisation strategies. Participant C2 explains that strategies '*can be set at a company level, or cost-linked companies with political integration, where they can track carbon emissions more easily.*' Also, they have '*access to sustainability personnel, they also run to lesser extent their own R&D facilities. It's easier to get capital because of this size. They have more options [...] in terms of R&D.*' They also have better access to international networks and can '*keep track of what's happening in the US and Europe.*'

Capital intensity

Increasing capital intensity (CI) is the ratio of capital investment to wages. CI has accompanied industry concentration and vertical integration across the three main groups. All of the companies in the three groups across raw material supplies, clinker and cement manufacturing and ready-mixed concrete manufacturing have invested in more technologically advanced plant and equipment. Plants have also been closed. This restructuring has supported considerable increases in labour productivity.

4.2.3 Concrete innovation

Innovation has been linked to reducing CO₂ emissions along the supply chain, from raw material mining to completed concrete structures, which is evident from the VDZ (2021) industry report. CO₂ reduction ‘assumptions are provided to demonstrate the important role the pathways can play across the Australian cement and concrete value chain’ for the period 2020–2050 (VDZ 2021:3). Eight pathways are nominated (VDZ 2021:8):

- zero emission electricity and transport (reduce by 14%)
- design and construction innovation (reduce by 21%)
- concrete innovation (reduce by 10%)
- increase use of supplementary cementitious materials (SCMs) in concrete (reduce by 3%)
- new CO₂-efficient cements (reduce by 7%)
- alternative fuels and green hydrogen (reduce by 6%)
- measure concrete take-up of CO₂ (reduce by 6%)
- capture remaining CO₂ (reduce by 33%).

Other initiatives indicate work on innovation, through academic research, professional association reports and declarations, company reports and ventures focussing on practices, processes, techniques, products and services.

In Australia there is new investment in R&D through the CSIRO and universities, as well as through cooperative research centres (CRCs), including:

- Heavy Industry Low-carbon Transition CRC
- Race for 2030 CRC
- Smart Crete CRC
- CO₂ CRC.

These CRCs are linked to similar extensive European and US initiatives. The VDZ report (2021: 33) identifies 10 areas for future R&D priorities and projects linked to current national and international R&D. Similarly, the GCCA (2021: 18) advocates in a global context for ‘R&D and innovation through public funding and risk sharing investment mechanisms’.

The concrete industry also recognises that there is more to innovation than R&D (VDZ 2021). First, there is an interest in industry policy support for decarbonising cement and concrete manufacturing and international competitiveness. Carbon pricing policy is not referred to by VDZ (2021). In contrast, the GCCA (2021: 18) includes carbon pricing in its policy framework by noting that ‘carbon pricing schemes exist in many regions of the world, and several of these cover the cement industry’ and ‘supports the use of market-based carbon pricing to incentivise decarbonisation at the lowest cost’.

Second, producing net zero CO₂ cement and concrete requires the cooperation of actors along the supply chain. Similarly, the GCCA (2021: 18) recognises the importance of cooperation by proposing to establish ‘climate innovation hubs which foster the participation of all relevant stakeholder groups’.

Establishing actor group agreement along the supply chain will require different drivers, as the interests and capacities of the actor groups that constitute that supply chain differ. For example, clinker producers have the potential to make savings by investing in technologically advanced plant and equipment, and they could make savings by reducing emissions if carbon pricing applies. However other actor groups such as building contractors and built-environment professionals, which are loosely coupled, have different access to resources and respond to different incentives (Dorée and Holmen 2010; Dubois and Gadde 2002).

4.2.4 Concrete industry institutional challenges

It is clear from the wider information that the leadership of the cement and concrete industry recognises that decarbonisation is required. Accordingly, there is broad agreement on the types of measures required to decarbonise the manufacture of cement and concrete aggregates:

- more efficient use of cement and concrete
- decarbonise cement and concrete production
- reuse of waste and use of industrial wastes from other industries
- decarbonise production and transport energy use
- carbon capture and storage (CCS).

Six institutional challenges are identified and briefly discussed below.

Construction professionals

Increasing the demand for lower-carbon concrete in the construction industry depends on the professionals involved in the design, specification and construction of buildings. They need to know how to design efficient structures and specify lower-carbon aggregates. There is evidence that professionals act conservatively because they have not been trained to design and specify low-carbon concretes (ICE 2022).

Similarly Lehne and Preston (2018: iv) and Gieseckam, Barrett et al (2015) observe that architects, clients, structural engineers and contractors are cautious about using novel building materials, which could suggest that the workforce is not sufficiently prepared to shift practices. An insider observes that there is a similar problem in the Australian industry:

[The industry] tends to import technical people to fill a gap rather than develop their own.
But there is certainly a need to attend to skill development because it's one of the planks of a decarbonisation strategy. (Participant C2)

A strategy proposed by the International Energy Agency (IEA 2018: 52) in a response to the lack of knowledge and expertise in the industry is to work with universities to 'train engineers and contractors to use different types of cement and to get a better understanding of sustainability issues related to building materials'.

Standards and regulations

In the cement and concrete industry, the primary standard is AS 3600:2018 Concrete Structures. It sets minimum requirements for the design and construction of concrete building structures. Its provisions are supported by references to another 46 standards.

Globally, there is considerable debate about future standards development. Key issues slowing progress in development relate to the prescriptive nature of the standards, as they:

- require use of familiar and accepted high-carbon cement and concrete recipes for particular applications
- reduce producer product innovation and competition, and reduce price competition

- require testing new recipes and applications using prescribed but inappropriate tests that take time
- require revision, but take a long time for the interests represented on the standards committees to research issues, discuss and compromise (Favier, De Wolf et al. 2018; Habert, Miller et al. 2020; Lehne and Preston 2018).

In Australia, the way the standard governs industry behaviour is a problem:

We are sitting here with a national construction code and a derivative set of standards that do not allow these [new cement and concrete] materials to be used. If you want to use these materials that's all fine. But, sorry guys, you're carrying the risk ... Risk escalates cost in the construction industry and precludes against using these materials. (Participant C2)

But change is on the horizon. Since 2018, the AS3600 standards committee has had a subcommittee working on a technical specification for lower-carbon cement and concrete products and structures. However, when the new specification does become a part of the standard it '*won't fully solve the risk issue, because there will be a continuing perception of risk, but it will minimise it and perhaps will support greater use of these new materials'* (Participant C2).

Market for low-carbon concrete

A market for low-carbon concrete (LCC) has begun to develop. For example, Boral offers three low-carbon LCCs: Envirocrete, Envirocrete Plus and ENVISIA. There is no publicly available data on the volume of LCCs in this small but emerging market. The question then becomes: how can this market be encouraged to grow? Two institutional features of the cement and concrete supply chain suggest there are two areas for action.

First, as already noted, the cement and concrete industry globally and in Australia is dominated by a small number of large companies. One of these is an overseas global company. Globally, international companies account for approximately a third of global cement production. This concentration of ownership in Australia and globally presents an opportunity for driving a broader decarbonisation agenda. Lehne and Preston (2018: 40) argue that 'the concentration of the global cement market means that a handful of major producers have particular agenda-setting power'.

Evidence of this power was apparent when business leaders of 10 global cement companies signed off on the first agenda for action in 2003 and formed the CSI which later became the GCCA (WBCSD 2003; GCCA 2021). Beyond agenda-setting, 'these firms have the resources to interact with standards committees and other institutions that set guidelines; they are therefore in a good position to help create and maintain norms and regulations' (Lehne and Preston 2018: 40). Of course, if these companies are to lead, there must also be institutional arrangements supporting their engagement with other actors in the supply chain, government agencies, standard-setting organisations and civil society organisations.

Second, public procurement can provide extensive support for the manufacture and use of LCCs. All governments in developed countries have large procurement programs. These include large construction programs that provide both economic and social infrastructure, which provides opportunities to support low-carbon innovation—including the use of LCCs (Baron 2016). In Europe, the role of procurement in supporting a broad sustainability agenda has been formalised through the adoption of a Green Public Procurement policy (European Commission 2016).

In Australia, using procurement to reduce embodied carbon in building materials—including cement and concrete—is only beginning to be considered as part of recent sustainability commitments. However, there are some within the industry that are making the case for using procurement to assist the cement and concrete industry develop its capacity to deliver LCCs.

Transparency and product disclosure

Environmental product declarations (EPDs) developed in the late 1990s. They have become the standardised way to present information on the environmental performance of construction products and services. An EPD is effectively a product certification system. Performance is assessed by using LCA, which requires that 'all the main inputs to the processes that provide the service are taken into account, as well as the processes and materials that feed into those processes, and so on back "up" the supply chains of the various materials in the product to the raw resource inputs' (Horne 2009).

The EPDs are based on the international standard ISO14025. In the case of building and construction products they also align with the European standard EN15804 (Passer, Lasvaux et al. 2015). EPDs potentially aid generating data that supports building-level assessments. However, further development of reporting requirements and improved data consistency is required for whole-life carbon footprint assessments and the setting of thresholds and targets (BPIE 2021). The use of EPDs in the Australian building and construction industry is voluntary.

The first concrete EPD was registered in 2014 by a New Zealand company: Allied Concrete. The next step was the 2017 publication of data that could be used in LCA calculations for Australian concretes. This was the product of a collaborative process, where the main industry players pooled data while maintaining commercial in-confidence concrete recipes. Then in 2019 Holcim began publishing EPDs. The reason they did it was because their '*international parent decreed that everywhere in the world Holcim was going to have EPDs ... Zurich told them that they had to do it'* (Participant C2). After this, the other major companies produced EPDs, and more recently some smaller companies have followed. '*It is like a game of dominos.*' Also, for major projects, having an EPD '*is now a requirement of supply*' (Participant C2).

The steps beyond the production of EPDs in Australia are uncertain, as there are no moves to include embodied carbon provisions in NCC revisions. However, the NSW Building Commissioner is signalling interest in whole-life carbon footprint assessments: '*I believe we are looking at the opportunity of, within a year, having the technology to accept, for every single building, an actual carbon certificate for every piece [of material] that goes towards a building*' (Frew 2021). The technology referred to is the development of an industry capacity to establish a system that holds a digital as-built record of buildings where embodied carbon could be included (Perera, Jin et al. 2021)

Carbon capture and storage

Globally and in Australia, the cement and concrete industry are relying on carbon capture and storage (CCS) in their commitments to decarbonise. As a process, CCS captures the CO₂ gas, then compresses and transports it to a site where it can be pumped and stored underground for geological time periods. The CCAA (2021: 10) states that efficiency measures will not '*reduce CO₂ emissions from the calcination of the limestone. Breakthrough technologies must therefore be implemented in which carbon capture will play an important role.*'

This has led to CCS pilot projects being established and goals being set. The CCAA (2021) foreshadows pilot projects, but to date no CCS pilot projects have been established in Australia by the cement industry. Although the industry continues to advocate for CCS and commits to confirming the use of CCS in their roadmaps, both the technologies (Voldlund, Gardarsdottir et al. 2019) and costs (Gardarsdottir, De Lena et al. 2019) continue to be assessed.

Uncertainties have led some people to propose radically changing the accepted concrete chemistry model as a way of reducing CO₂ emissions. One method is to significantly reduce the proportion of manufactured clinker cement and replace 50 per cent of it with calcined clay—which is clay that has been heated to a high temperature—and ground limestone to make limestone calcined clay cement or 'LC3' (Habert, Miller et al. 2020). Another method is to cease using cement made from manufactured clinker altogether. Instead, the concrete aggregate is made from sand, gravel, clay, silts and organic plasticisers (Ouellet-Plamondon and Habert 2016).

Costs of abatement

Decarbonising the cement and concrete industry will require new investment in plant and equipment, and will increase recurrent costs. Three main measures have been identified by the industry (CCAA 2021: 31). They are:

- further substitution of clinker in cement by supplementary cementitious materials (SCMs) through increased use of fly ash, ground granulated blast-furnace slag and clays
- replacing the use of coal and gas fuels with biomass fuels and green hydrogen
- using CCS.

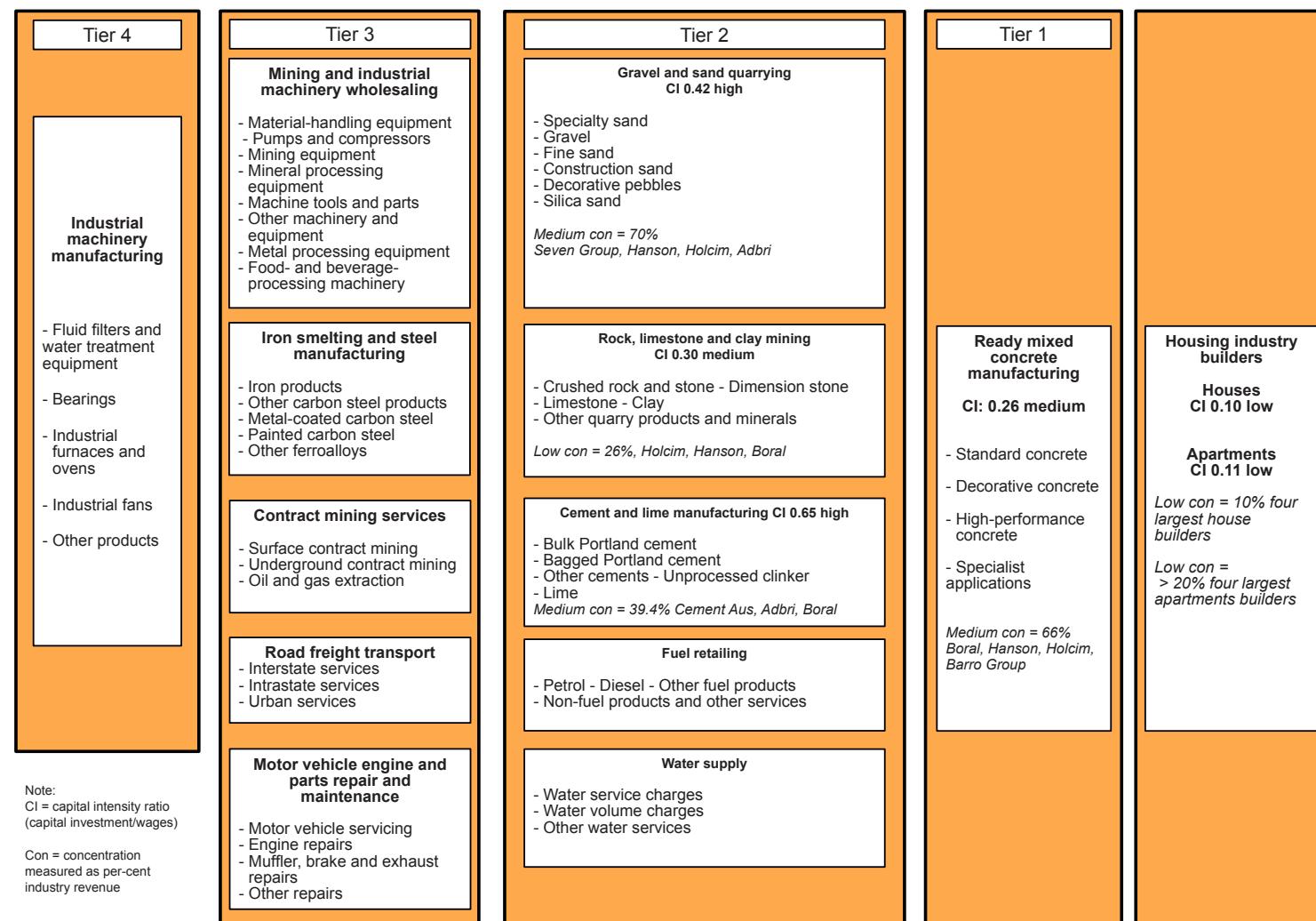
The pathway for the first main measure (substituting clinker) is clearer than the second or third measures. Estimates of investment and operational costs depend very much on plant-specific analyses, which have not been done in Australia. The only estimates available are indicative figures developed in Europe (ECRA and CSI 2017).

How these increased costs will be met is yet to be determined, but it is likely to be through a combination of industry and government investment. Investment by the federal government was first signalled by DISER (2020), which recognised cement as a carbon-intensive product. Following the 2022 change of government, all that is available at the time of writing is the ALP policy platform, which committed to a National Reconstruction Fund that would assist with the decarbonisation of existing industries (Australian Labor Party 2021).

A cost that the industry may well have to bear is meeting a price on carbon triggered by the ‘revised baselines’ (Australian Labor Party 2021) referred to in subsection 4.2.1. A price should encourage the industry to continue reducing carbon emissions. Participant C2 sums up the effect: *‘a carbon price will generate a revenue stream that can be invested in measures that reduce emissions and the price’*.

An important factor in calculating and pricing carbon emissions will be how to recognise the emissions associated with imported clinker. If decarbonisation measures required in Australia do not apply in the countries that are exporting clinker, then there will be a case for border-adjustment measures—similar to those being developed by the EU and other countries that are ramping up their climate mitigation commitments (Muller, Saddler et al. 2021). It is likely that clinker manufactured in Australia and attracting a charge for emissions will be more expensive than clinker imported from countries that do not put a price on CO₂ emissions. The CCAA (2021: 45) warns that ‘federal and state government policies and programs will be required in order to maintain the international competitiveness of the industry’. Maybe border-adjustment measures for clinker imported into Australia is such a policy.

Figure 14: Concrete industry supply chain



Source: Authors based on IBISWorld industry reports.

4.3 Steel

Steel is used in both the HCl and MUATCI residential housing sectors. The manufacture of this steel starts with companies in the Iron Smelting and Steel Manufacturing Industry (ISSTM), as shown in Tier 3 of Figure 15. Four downstream industries manufacture products, which then make their way into residential housing construction through industries providing onsite supply and construct services. Large amounts of embodied carbon in steel stocks are already in the housing system, and additions are important for decarbonisation and the development of a CE. The carbon intensity of steel is now well recognised by the steel industry in Australia and globally.

In the HCl market, there are two main types of construction, and both use steel:

- The first and most dominant type is timber-framed housing, where the stud wall frame and roof trusses are timber. Steel is used in the reinforced concrete waffle slab cast on the ground, in some structural beams and posts, and in products such as sheet-metal flashings, garage doors, gratings, balustrades, railings and roofing.
- The second type is steel-framed houses, where cold-formed steel replaces timber wall frames and roof trusses. All other uses of steel are the same as in timber-framed houses.

Growth in steel-framed house construction began following the formation of the National Association of Steel-framed Housing (NASH) in 1982, and incorporation of steel framing provisions in the NCC (Paton-Cole and Gad 2017). The share of houses built with cold-formed steel in 2017/18 was 14 per cent (ACI 2018: 9). However, much of the growth tends to be in northern Australia because steel framing is termite proof (Participant S3). There are recent indications of growth in the use of steel framing because of timber shortages.

The MUATCI dwellings are the greatest user of steel, as apartment buildings are usually constructed using reinforced concrete. Together the EE from steel and concrete result in buildings with a high EE coefficient (Li, Foliente et al. 2021), which increases the carbon intensity of Australian housing. Further, the uptake of two other less carbon-intensive construction types is languishing:

- Lower-carbon mid-rise could be built using cold-formed steel to construct lightweight apartment buildings. However, there has been no uptake of this system in Australia—in contrast with the UK, the US and Canada (Franklin 2019).
- Structural timber can be used to construct low-carbon mid-rise apartment buildings (Jayalath, Navaratnam et al. 2020). Yet uptake of structural timber for mid-rise apartment buildings in Australia has been minimal.

Australian participation in the carbon-intensive steel industry is considerable. Australia is the world's largest producer of iron ore, representing 39 per cent of global production—of which 95 per cent was exported. In 2021, Australia ranked 29th out of 50 steel-producing countries, with 5.8 million tonnes of crude steel production and 0.3 per cent of world steel production (WSA 2022). Australia is therefore a major player in the global steel industry, and is in a unique position to contribute strongly to an emerging global green steel industry (Venkataraman, Csereklyei et al. 2022). The contemporary challenge is how to transition from a fossil-fuel-based blast-furnace technology to 'green steel' technology.

4.3.1 Carbon in steel

Steel production produces between 7 per cent and 9 per cent of GHG emissions (WSA 2021). Tier 5 iron-ore mining and coalmining businesses (see Figure 15) contribute a large share of Australian steel industry CO₂ emissions. Steel is produced by reducing iron ore to iron ('ironmaking'), removing carbon, secondary refining and alloying ('steelmaking') and continuous casting. Three fossil-fuel-based production processes are available to the steel industry: blast furnace, direct-reduced iron, and smelting reduction (Venkataraman, Csereklyei et al. 2022). These arrangements are no longer sustainable. Meanwhile, global demand for steel continues to increase.

Companies using fossil-fuel-based production processes have lowered their emissions through technological improvement, particularly the smelting reduction technique. There has also been less reliance on emissions-intensive primary iron-ore production, with a move towards cleaner secondary production using scrap steel (Winning, Calzadilla et al. 2017). However, further substantial emission reduction is required. The IEA (2020: 53) states that the industry, if it is to be 'compatible with the goals of the Paris Agreement, its direct CO₂ emissions must fall by more than 50 per cent by 2050 relative to today'. The steel industry's response has been two-fold.

First, the global industry association, the World Steel Association (WSA 2021), has committed the industry to reducing CO₂ emissions by 'transforming steel production'. Signalled headline measures are:

- efficiencies in production
- maximising the use of scrap metal
- developing and deploying breakthrough low-carbon technologies
- material efficiency in the use of steel
- advanced steel products.

Second, reducing emissions requires a governance framework for measuring and assessing decarbonisation. Two initiatives have contributed to the framework:

- The Responsible Steel (2021b: 65) standard sets up requirements for GHG measuring, reporting and target setting at the site level.
- The Net-Zero Steel Pathway Methodology Project (TWG 2021) is a broader framework that extends to supply-chain arrangements based on LCA and includes setting system boundaries and apportioning emissions from co-produced products.

The two major Australian steel manufacturers, BlueScope and InfraBuild, have made commitments to reduce their GHG emissions. Between 2005 and 2021, BlueScope Steel reduced their GHG-steelmaking emissions by 40 per cent. Further, BlueScope has committed to another 12 per cent reduction by 2030 and net zero by 2050 for its flat steel production (BlueScope 2021a). InfraBuild has committed to a new range of more materially efficient high-strength reinforcing steels, resulting in a 33 per cent reduction in mass compared with standard fitments (InfraBuild 2020).

Use of scrap steel in new steel production reduces emissions, and all steel production uses scrap. While some projections anticipate that recycled steel could fulfil future demand in steel there are two issues.

First, the availability of scrap steel is a constraint (WSA 2021).

Second, contaminants limit the use of recycled steel for certain products, such as reinforcing bars in the construction industry (Daehn, Cabrera Serrenho et al. 2017; Venkataraman, Csereklyei et al. 2022). Despite these limitations, scrap recycling will be critical for carbon reduction in the future. Winning, Calzadilla et al. (2017: 405) argue that steel has CE potential because of its 'potential double environmental benefits of increased secondary steel production which also uses low-carbon electricity as a significant input'. Participant S3 confirms the importance of scrap for reaching the BlueScope target: '*how are we going to hit that 12 per cent? It's increased renewables [renewable energy] and scrap has a big impact.*'

While progress is being made, the full scope of measures needed for decarbonisation requires change in the way that companies produce steel, along with broader system, industry and societal change. A review of the BlueScope (2021b) strategy suggests a series of measures for change (see Table 11). However, it is important to note that BlueScope is silent on the possibilities of a price on carbon or regulation.

Table 11: Steel decarbonisation: BlueScope view of societal and company change

Buildings, industry, societal change	Company change
<ul style="list-style-type: none"> Buildings: modular design, heritage structure reuse, efficient material and design Extend building lifetimes Recycling market for scrap Non-steel outputs as co-products: fly ash, slag, chemicals, dust and sludge, emulsions Renewable energy growth 	<ul style="list-style-type: none"> Transparency through EPDs Organisation development: climate groups Collaboration: civil society collaboration Product development: lightweight long-life broad use Further energy and process efficiencies Low-carbon energy use increase Scrap use increase Current operating asset optimisation Decarbonisation capital raising and allocation Breakthrough technologies: hydrogen from renewables and electrolytic reduction

Source: BlueScope (2021a; 2021b)

4.3.2 Steel industry structure

Two companies, BlueScope Steel and Liberty InfraBuild, dominate the ISSTM industry (Baikie 2021b). BlueScope Steel has a 41.1 per cent market share. It manufactures 3 million tonnes of flat steel per year into products such as Colorbond and Zincalume for cladding and Truecore for steel framing in integrated steel plant in Port Kembla, NSW, using blast-furnace technology (BlueScope Steel Limited 2021). Liberty InfraBuild has a 6 per cent share of the market, and manufactures steel long products, including reinforcing bar, reinforcing mesh, tubular and hollow sections, merchant bar and wire. Liberty operates an integrated steel plant in Whyalla, SA. It also recycles scrap steel at two sites in Australia. The scrap-steel operation feeds 1.4 million tonnes of steel per year into InfraBuild steelmaking (InfraBuild 2021). The rest of the ISSTM industry is comprised of many small to medium enterprises (Baikie 2021b).

The structure of the ISSTM (Figure 15) can be understood by focussing on three dimensions: concentration, vertical integration and capital intensity.

Concentration

Industry concentration in the ISSTM industry is moderate, based on the 47.1 per cent market share of industry revenue flowing to the two main manufacturers. The industry is also highly globalised. InfraBuild was taken over by the British GFG Alliance in 2017. BlueScope, an Australian-owned company, distributes products into North America, ASEAN countries, New Zealand, the Pacific Islands, China and India. Baikie (2021b: 39) notes that 'over 80 per cent of the industry's enterprises employ fewer than 20 people and only 20.0 per cent of businesses generate over \$2.0 million in revenue, annually'.

Vertical integration

Industry concentration is associated with a degree of vertical integration. InfraBuild achieves this through its upstream iron-ore mining operations and downstream steel-tube manufacturing capacity. The BlueScope strategy has been to develop strong brand identities for its products. Additionally, BlueScope has internationalised the market for these products to the countries noted above, and developed strong downstream market relationships. In the US, this has occurred through the development of strategic alliances with related sector enterprises (Fairgray, Tamásy et al. 2012). In Australia, the market relationships are with manufacturers in the Tier 2 and Tier 1 manufacturing industries. BlueScope has a strong presence in one of these industries: the manufacturing of metal roof and guttering (Martin 2022). This is the context for the Australian Competition and Consumer Commission (ACCC 2019) successfully taking action against BlueScope for alleged cartel behaviour, on the grounds that BlueScope sought to induce Australian steel distributors and overseas manufacturers to enter agreements containing a price-fixing provision.

Vertical integration is being extended with growth in steel-framed houses produced by manufacturers with roll-forming machines and erected by frame installers. This has led to a small well-established industry. However as the industry association NASH states, 'steel framing is not an easy industry in which to flourish ... Steel framing looks easy, but it is a major mistake to underestimate the difficulties inherent in the industry' (Watson 2005). One issue is undercapitalisation, where steel availability often becomes an issue, as indicated by this stakeholder:

There are similar builders who have bought roll formers before allocation, but only just getting their foot in the door and starting to do some of the light-gauge steel, who are on allocation and only get one or two tonnes a month and could use 20 or 30 [tonnes]. (Participant S4)

Capital intensity

Capital intensity (CI) varies considerably across the supply chain industry (see Figure 15). The ISSTM industry has medium-level CI. However, the level has been increasing and continues as the industry has restructured and reinvested in furnaces and casting equipment. Recently, BlueScope stated that it is likely to invest a billion dollars relining a mothballed blast furnace, which will contribute to further decarbonisation of its steelmaking (Roberts 2022). One downstream industry, metal roof and guttering manufacturing, also has a medium CI and has been increasing as companies have continued to automate their production by increasing their capital intensity. BlueScope is the company in this industry with the largest market share, at 37.6 per cent. One other downstream industry in Tier 1, 'Structural steel fabrication' has a medium CI. BlueScope and Liberty have a combined 43.2 per cent market share in this industry, where they focus on higher-volume simple products suitable for automated production and fewer labour inputs (Kelly 2022d: 34).

4.3.3 Steel industry innovation

Globally, the steel industry recognises that innovation is central for the decarbonisation of steel production (Responsible Steel 2021a; WSA 2021). In Australia, the two largest steel industry companies reflect the global industry analysis and commitments by making significant civil society contributions. Four main directions for innovation come through from the global and Australian contributions to the debate on how best to decarbonise the steel industry. They are discussed in the following paragraphs.

Recycling and reuse

Steel manufacturing is environmentally intensive, yet it also allows for almost infinite recycling—and thus offers a perspective to innovate (Winning, Calzadilla et al. 2017). 'Every tonne of scrap used for steel production avoids the emission of 1.5 tonnes of carbon dioxide, and the consumption of 1.4 tonnes of iron ore' (WSA 2021: 4). If scrap recycling is carried out in an electric furnace, then the energy intensity of production is 12.5 per cent (an eighth) of what it would be from iron-ore smelting (IEA 2020: 16).

However, there are limitations to increasing the use of scrap steel. First, the availability of scrap steel is limited by the end-of-life rate of steel products. Globally, this rate correlates with the age of the steel structures and products in the capital stock of countries, which varies considerably. It is also shaped by other factors, in particular the willingness of owners to avoid recycling of existing steel structures and products by smelting and instead renew products and retrofit buildings.

Second, the effectiveness of the collection and sorting of steel for scrap is an issue. This is partly a price issue. As the IEA (2020: 30) notes, the availability of scrap increases along with price, but also depends on the cost of sorting scrap. Although there is the possibility of infinite recycling, there is also an issue about contaminants in scrap steel—especially copper (Daehn, Cabrera Serrenho et al. 2017).

The issue of recycling and reuse in the housing sector is connected to the broader issue of CDW. In this context, steel is just one material among many that are transported from a building or demolition site. Much of this transportation will be done using skips, where sorting is not required. The contents of these skips will likely end up in landfill unless the landfill charge or the price for recycled materials is high enough to create a market for separated materials and their recycling or reuse (Shooshtarian, Maqsood et al. 2020).

Recycling of scrap metal has only recently been receiving policy attention. Further, the policy attention and system development varies considerably across Australian state and territory jurisdictions, resulting in a complex field. A recent review reveals that there are at least eight areas of strategy development in scrap metal reuse:

- waste recycling
- illegal dumping and stockpiling
- extended producer responsibility
- definition of waste versus resource
- use of construction and demolition recycled waste
- energy from waste extraction
- education and engagement
- market development (Shoostarian, Maqsood et al. 2020).

Onsite, it is up to the builders to decide how they deal with their waste. One manufacturer supplying light metal frames for houses described his approach: '*Most of our waste, we use it as packing to go to site, so we don't have a lot of waste. We probably get rid of two or three tonnes a month*' (Participant S4). The broader arrangement for 'getting rid' of small offcuts was described:

Over the next five to 10 years, it will probably get better, and it needs to. From our perspective, all our stuff goes into a couple of bins from our punchings and small offcuts, it all goes back to recycling to the factory and [will] come back to us at some point. (Participant S4)

There is also the prospect of using 'evolving technology', which will further reduce waste by printing '*the top plates for location of trusses with truss numbers and everything on it, so that's pre-done, pre-controlled*' (Participant S4).

Green steel technologies

There is broad agreement that current blast-furnace technology innovation has reached its limit, and that full decarbonisation of steel only be accomplished by using what the World Steel Association (WSA 2021) calls 'breakthrough technologies'. The main elements being considered to contribute to early and later stage decarbonisation are:

- green hydrogen replacing coke as a reductant, generating H₂O instead of CO₂
- bio-resources to provide carbon to replace coke
- CCS with utilisation of the CO₂
- electrolysis using renewable electrical energy.

Similar to changes in concrete manufacturing, breakthrough technologies in steel manufacture 'will require major changes in manufacturing processes, use of alternative materials that do not emit CO₂ during manufacture, or CCS technologies to minimise the release of process-related CO₂ to the atmosphere' (Davis, Lewis et al. 2018: 4).

Although there is broad agreement about the elements required, debate continues about the change process and its timing. This is partly because the geography of existing steelmaking is linked to supply-chain arrangements and access to resources. According to Venkataraman, Csereklyei et al. (2022: 7), the two most prospective zero-carbon steelmaking technologies are hydrogen-based direct-reduced iron (DRI)—otherwise known as hydrogen-based steelmaking—and electrowinning, which involves extracting metals electrolytically from ore, 'both of which would ultimately require massive electricity infrastructure to supply the required primary energy input'.

For this reason, Australia has a competitive advantage, as the cost of energy will be 'critical to the competitiveness of green steel production' (Venkataraman, Csereklyei et al. 2022: 7) and the Pilbara region where most Australian iron-ore mining is concentrated benefits from extremely favourable solar irradiation. This, added to onshore wind resources, creates ideal conditions for reliable large-scale electrification—while at the same time lowering the costs of green steel production. However, scientists note that while most of 'these processes offer lower-carbon pathways for steelmaking', they 'cannot completely eliminate the associated emissions' (Venkataraman, Csereklyei et al. 2021: 3).

The challenge accompanying this program is the scale of investment required for the transformation.

First, there is the investment in the steel sector. One projection is that an investment of \$30 billion per year is required for the next 30 years, just to meet growing steel demand and maintain existing sites. Further investment of \$6 billion per year is then required to transition the steel asset base to net zero. Calculated in terms of avoided emissions, this is a cost of \$6 per tonne of CO₂ avoided.

Second, steel plants will require electricity to generate green hydrogen and electricity for their electrified assets. This will require an 11–13 times increase of current electricity use (Net-Zero Steel Initiative 2021: 8).

Industry collaboration

A transition to low-carbon steel production requires an industry transition involving levels of collaboration between firms and with governments, research institutions, industry associations and unions. Examples of current collaborations in the steel industry aimed at lower-carbon emissions are the:

- Australian Industry Energy Transitions Initiative (Climate Works Australia 2020)
- Global CO₂ Breakthrough Program.

Such initiatives run alongside continuing competition between firms producing similar products and seeking to maintain or increase their market advantage. In this context, the Australian Competition and Consumer Commission (ACCC) is keen to ensure that collaboration does not undermine competition.

Collaboration can also be global. An example is the work of Responsible Steel (2021b), a global multi-stakeholder standard and certification organisation, that defines agendas and procedures for projects such as the Responsible Steel Standard. Structured around 12 principles, it sets out requirements and criteria that are auditable at the company and site level. At the local level, these processes are regularly organised by industry associations. In the case of Australian Steel Institute, there is continuing work on an industry approach to decarbonisation. The basis of collaboration in the industry aimed at defining and setting common parameters for decarbonisation was outlined by Participant S3:

There is a lot more collaborating on [the question]: 'What does good look like for the steel industry rather than decarbonisation specifically [for one company]?' ... At the moment, we are trying to set what the thresholds look like for a piece of steel to be called responsible. How many tonnes of CO₂ per tonne of steel is good? ... Our focus is more on value, trade value-chain collaboration than competitor collaboration. (Participant S3)

Skills and practices: growth in light-gauge steel prefabrication

Entry into light-gauge steel house construction has few barriers to entry and tends to attract people with some building experience who are seeking to be self-employed small business owners. Initially, it involves procuring a roll former, a licence to use software programs to design and manufacture steel trusses and frames, and some experience as a builder. Computer-aided design (CAD), which was described by Participant S4 as a 'video game for chippies onsite', requires varying levels of knowledge and expertise, and requires the assistance of an engineer for the design of wall frames. One limitation slowing the use of steel prefabrication is regulation, with participants identifying more regulations around wall frames than trusses:

The trusses are self-certifying, so you can put a truss there and it'll draw it in long as you've got a couple of loadbearing points, it'll tell you whether it will work or not. You can change it, manipulate it as you see fit to try and get it to pass with the loads, and so on. Wall frames are a little bit different. We've got a design manual to work to. You need to sign off on it. The companies that buy those can send it off to get checked and certified and then come back, or they can employ an engineer to understand and do it. (Participant S4)

There are also opportunities for prefabrication and efficiency gains through transport and weight reduction. In this pathway, steel presents a competitive advantage in terms of weight compared to timber:

Ninety-nine per cent of the stuff that we do is prefabricated. And that's where the steel frames are probably better at. For the houses that we build for our two main builders, that are probably between 300- and 400-square-metre homes, we fill two semis with frames and trusses. Most timber-frame builders do probably 50-50 with their builds; their trusses are a little bit thinner than ours because we do back-to-back so we are twice as thick with the truss profile. So rather than being 35 mm, 45 mm, we are 80 mm. Their frames are similar, but our frames are probably about half the weight of timber ones. (Participant S4)

Beyond such accounts, there remains insufficient capabilities, training or experience in the assembly and manipulation of light steel on construction sites, where carpenters tend to rely on the extended experience with timber installation gained during their apprenticeship. The lack of training—and therefore ability to understand plans and instructions—becomes an issue when carpenters shift to light steel. Also, design and assembly differs between light-gauge steel and timber regarding the average level of qualification required.

4.3.4 Steel industry institutional challenges

The Technical Working Group (TWG 2021) describes the steel sector as 'hard to abate' for several reasons:

- Steel production relies on fossil fuels, long-life capital-intensive assets and a long investment cycle—between 25 and 40 years.
- Steel is a global commodity with high competition, low selling prices and low profitability—which reduces investment potential (TWG 2021).
- Despite technological innovation and new investment, continuing high rates of urbanisation mean there will be continued demand for virgin steel.
- Less carbon-intensive technologies are not yet developed sufficiently for large-scale asset renewal (Venkataraman, Csereklyei et al. 2022).

The steel industry is a carbon-intensive industry, so the extent and nature of the discussion with the finance and insurance sector also matters in terms of how it plans to:

- mitigate climate change risks
- finance the reconfiguration of steel production.

The industry modes of production also present some challenges in understanding the material flows that go into steel production. There are some issues from a data perspective (see Section 2), which mean it is more difficult to design for deconstruction:

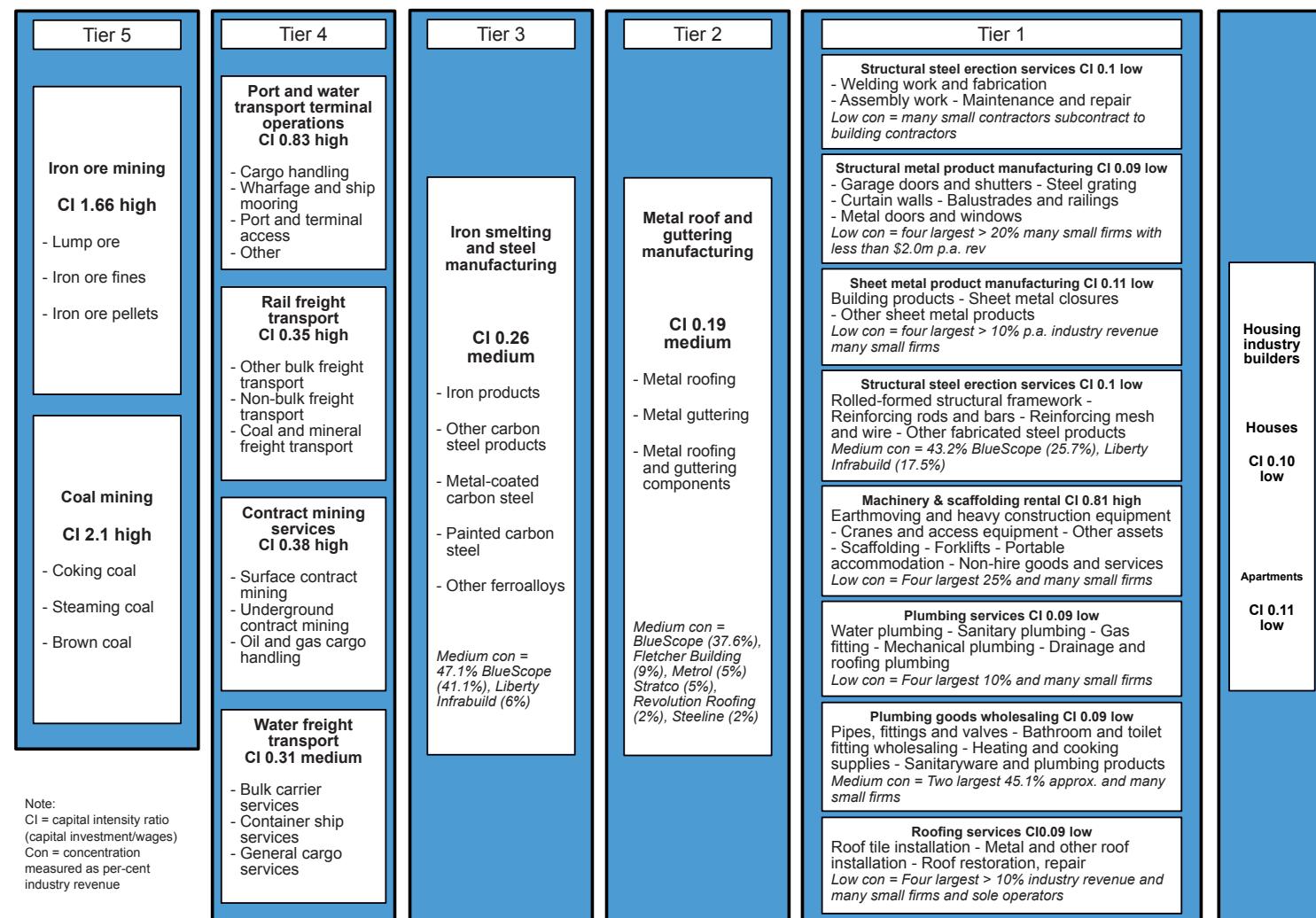
At the producer level, there is the ability to see aggregate production, but then quickly there are channels where other players get involved in transforming it, and then distributing or installing it. If the producers don't need to know the distinction, they have not invested time to interrogate it. (Participant S2)

Finally, the Australian steel industry is acutely aware of the competition from alternative materials and substitutes and their related industries for a transition to low-carbon housing in Australia. In particular, residential steel products are competitively positioned against sawn timber and engineered wood products (EWPs) and timber framing in the residential sector.

While there is growth in the volume of steel products, it is difficult to estimate the supply of steel products for residential construction. Participant S3 estimates that in 2018–2019, about 12–13 per cent of steel production was going into the residential housing industry, and there was an increase of about 2 or 3 per cent in the five years prior to that. Thus the steel industry is slowly positioning itself to venture into the mid-rise residential space, a sector that continues to increase in Australian residential housing construction despite the competition from concrete and the need for additional training or adaptation of steel-installation techniques:

[A steel roofing product] is probably not something that we would probably work towards for mid-rise, typically because it's generally concrete anyway, and probably not fit for purpose in that space. So it's not something that we have entertained too much. There are aspects of cladding for mid-rise in [name of product] that we are looking into, a lot of our channel members being installers. They do have a bit of that coming through. (Participant S3)

Figure 15: Steel industry supply chain



Source: Authors based on IBISWorld industry reports.

4.4 Timber

Timber is a low-emission biomaterial that is used in both HCl and MUATCI residential housing. Timber manufacturing starts with forestry primary production in Tier 4 businesses (see Figure 16). The product then goes downstream to Tier 3 manufacturing industries, including log sawmilling and timber wholesaling. In Tier 2 businesses, the timber resawing and dressing industry are engaged in importing timber, which represents approximately 20 per cent of annual timber supply (Woods and Houghton 2022). Businesses in Tier 1 industries manufacture a wide range of products and provide services to the housing industry.

The wood product industry supplying the housing industry is structured around two supply chains:

- **Lightweight timber sawn from lumber**—‘*a lightweight chain that is very commodity-driven*’ (Participant T9). Lightweight timber is used for residential ‘stick building’, which uses small-dimension timber for trusses, wall frames and floors. The more air there is in the structure, the cheaper and less solid it is.
- **Engineered wood products (EWP)**—including ‘mass timber’ in forms such as cross-laminated timber (CLT), glue-laminated timber (Glulam) and laminated veneer lumber (LVL). EWPs are manufactured, and are more expensive than lightweight timber and ‘*a totally bespoke value chain*’ (Participant T9). These products are made from the same hardwoods and softwoods as sawn timber, but mixed with adhesives that bind the strands, particles, fibres, veneers or boards. This product often incorporates treated sawmill waste to produce wood that meets precise size requirements.

Starting with the low-emission biomaterial property of timber, some groups in the timber and housing industry argue that timber used in residential housing construction can make a significant contribution to decarbonising the housing industry. This argument underpins a long-running project advocating for greater use of timber. The first step was to successfully advocate for reform of the NCC to support the inclusion of deemed-to-satisfy provisions for building timber structures up to 25 metres in height, or eight to nine storeys. A second step was establishing the Wood Solutions Mid-rise Advisory Program, which supported design professionals and the housing industry to expand timber use in residential housing construction (Lavisci 2020; Wood Solutions 2023). Perinotto (2022) suggests that ‘there’s an information war going on between advocates for timber, concrete and steel, and everyone is claiming their material is the best from an environmental perspective’.

4.4.1 Carbon in timber

The focus on embodied carbon in buildings has led to research advocating for greater use of timber rather than concrete or steel (see Campbell 2019; Carvalho, Jorge et al. 2020; Churkina, Organschi et al. 2020; Gu, Liang et al. 2020; Hafner and Schäfer 2017; Jayalath, Navaratnam et al. 2020; Lu, Hanandehet al. 2017; Perry, Pechey et al. 2021; Robati and Oldfield 2022; Thomas and Ding 2018).

For example, Robati and Oldfield (2022) compare timber and concrete buildings and find that mass timber buildings generally have lower-embodied carbon than concrete buildings. Similarly, Jayalath, Navaratnam et al. (2020: 1) state that the ‘use of 17 per cent of timber in construction as an alternative to brick, aluminium, steel and concrete, can reduce GHG emissions by about 20 per cent’.

Some actor groups are using this research to argue for timber being used more often as a structural material and, at least in part, replacing concrete and steel. They argue that by growing trees, which sequester atmospheric CO₂, using structural timber in building construction can act as carbon sinks (Churkina, Organschi et al. 2020). One of the benefits of trees and timber harvesting, just like other biomaterials, is their capacity to ‘use photosynthesis to convert atmospheric CO₂ into oxygen and sugars, the latter of which is stored as carbon in the material biomass’ (Robati and Oldfield 2022: 2). Robati and Oldfield (2022: 2) argue that timber housing strategy in Australia could ‘reduce built environment life cycle GHG emissions by 94 per cent at a national scale, compared to business as usual’.

Despite this emerging research, there is as yet no developed and agreed strategy endorsed by timber industry actors in the extended supply chain. Participant T9 suggests that the timber industry is 'highly conflicted'. For example:

When it comes to a carbon tax, if you're a large processor, you have electricity bills. You only see a carbon tax as a cost. Rather than seeing it inflicting costs on your competitors, they only see it through the lens of adding costs to their business. (Participant T9)

There is also no agreement about the accounting system used to measure and record carbon in timber in any carbon accounting system. That lack of agreement is evident in the divide between the primary and secondary producers in the supply chain:

The plantations get a credit, but the builder gets nothing. The government looks at this at a national level and ... from an accounting point of view divides the economy into eight to 10 sectors [as] ... they don't have the policy rules that are cross-sectoral. And they can't do that through carbon price. (Participant T9)

At present the system is limited because '*you can only achieve net zero through forestry, not by using wood products*'. It only supports '*planting more trees or avoiding emissions from other materials*' (Participant T9). Similarly, if imported timber is used, the only benefit is in those avoided emissions from the other materials. There is no equivalent protocol for system-wide carbon accounting in the timber industry as in the steel industry (Responsible Steel 2021b).

The response proposed by Robati and Olfield (2022: 14) is to 'stop framing embodied carbon as a static upfront carbon impact'. Instead, embodied carbon should be understood as 'dynamic and temporal', which requires accounting across the building life cycle, including end-of-life.

4.4.2 Timber industry structure

Industries in the timber supply chain, with two exceptions, are characterised by low-level industry concentration. The exceptions are two Tier 1 manufacturing industries—Fabricated wood and Prefabricated building—and Tier 3 and Timber wholesaling with medium concentration. The most significant is Fabricated wood, where the three largest companies have 60 per cent of the market share (Kelly 2022a). Similarly, capital intensity through the supply chain is generally low. Only Forestry and logging, Timber wholesaling and Prefabricated building have medium capital intensity.

In other words, there are no large dominant players as there are in the steel and concrete industries. It is a less capital-intense industry dominated by SMEs. Participant T9 summed up the implications of this structure for the timber industry in relation to R&D and innovation:

No one has R&D capacity, unlike the property-sector firms like Stockland, Mirvac and Lendlease. They are not developers—they are machines. And because you're a machine, you have to constantly be ahead of the game. [...] The big boys have a very different operating model than the small guys. (Participant T9)

This fragmented low and medium industry concentration is also reflected in the number and diversity of industry and professional associations.

Industry and professional associations

The timber industry has many industry associations formed by companies making particular wood products, such as the Australian Glass and Windows Association, Frame and Truss Manufacturers Association, Engineered Wood Products Association of Australasia, Kitchen Cabinet Manufacturers Association, Australasian Timber Flooring Association, and Australian Timber Importers Federation. In Tier 4, the Forestry and logging industry, the associations are geographically aligned, such as the Victorian Forest Products Association and Timber Queensland. This pattern relates to the history of forestry, where access to hardwood forest timber was governed by state government statutory authorities:

Each state was run like an old feudal system where the department provided licences and they used to have a statutory role for someone to represent the licensees in their negotiations on the price of logs to the sawmills. (Participant T1)

What is missing from the timber industry, compared to industry associations in the steel and concrete industries, is a large pan-industry association able to establish a shared industry identity and resource the development of industry strategy from the forest through to manufacturing. Further, the current configuration of associations does not support international linkages. Rather, broader industry leadership is provided by two organisations:

- **Australian Forest Products Association (AFPA)** is the national industry body representing the resources, processing, and pulp, paper and bioproduct industries covering the forest-products value chain. It starts with the forestry end of the supply chain and focuses on the bulk commodity products. It does not extend to the Tier 1 manufacturing industries.
- **Forest and Wood Products Australia (FWPA)** is not an industry association, but is one of 15 rural research and development corporations (RDCs) supported by the Australian Government and by levies paid by wood processors, forest growers, and forest-products importers. FWPA research expenditure receives matching government funds.

The outcome is summed up by one participant, who argued that the problem is that strategic thinking is '*threadbare*' (Participant T1). The relatively small industry associations focus on servicing their members and do not have the resources to develop broader industry strategy: '*In the old days, they might have been strategic in a parochial sense, but these days there's no strategic thinking*' (Participant T1).

Wood supply and plantations

Australia has few comparative advantages for forestry and plantations because it has relatively poor soils and a history of policy failures governing the use of hardwood forests and the development of plantations. Instead, there is a need for a strategic, long-term roadmap that increases tree-growing to compete with countries equipped with better soils, more rainfall and climates that produce '*those nice straight fur type trees, like spruce and Baltic trees, that get used a lot in construction*' (Participant T1). At present, Australian tree production is more expensive, as Participant T1 explained:

At the very economic base of the Australian timber industry, there is the stumpage cost. The cost of the Australian log at the tree stump is higher. It's great to have significant plantations, but in a pure global perspective, if our economy is up, and their economy is really going, we're building a lot. If other economies are down, timber tends to be a bit cheaper even with all transport costs. (Participant T1)

Government interventions supporting tree-planting began in the 1870s in regions with little local supply (DAFF 2008). After that, state governments established the first softwood plantations. It was not until 1997 that Australia developed its first plantation policy and supported large-scale native eucalyptus plantations. *Plantations for Australia: The 2020 Vision*, developed by federal, state and territory governments, supported expanding the plantation estate to 3 million hectares by 2020, and included a processing industry. However, for Participant T1 this policy design was flawed:

Under the Howard government, there were primary-industry tax concessions. Unfortunately, it brought about fairly one-sided businesses that were investment-based businesses that planted trees, instead of establishing plantation-based businesses, like Timber Corps, FEA, the Great Southern Plantations. They were using a tax benefit, but it didn't really create enough productive plantation because they were getting an eight-year return from the blue gums—*Eucalyptus globulus*. You can harvest that in eight years, but they were looking for fast turnaround. (Participant T1)

Subsequent growth in plantations has slowed over recent decades.

The forestry portfolio currently sits within the Department of Agriculture, Water and the Environment (DAWE), an ambivalent position in government according to Participant T1:

Growing trees, obviously that's primary production. But turning the trees into finished products is primary processing. And that's quite sophisticated. [...] So it's a bit like, 'Well, you take a tree, we don't see that as high-tech manufacturing.' But in fact everything to do with turning a tree into finished products is high-tech manufacturing. But, yes, we sit within agriculture. (Participant T1)

Subsequent efforts to have forestry recognised for the development of Industry 4.0-driven manufacturing has not been successful, and this has limited advanced manufacturing in the timber industry:

They've created these centres of excellence around manufacturing, and we've turned up to those structures and said, 'We're forestry, we'd really like to do some stuff around big data and sawmilling.' And they go, 'You're not food manufacturing, so we're not interested.' (Participant T1)

Supply chain lock-ins

The residential-housing-industry supply chain is structured in a way that enables some actors to control how wood is used. In effect, it disconnects timber producers from end users and prevents change and innovation along the supply chain. As Participant T1 put it, '*[the growers] are divorced from the market*'. Two struggles over supply-chain arrangements illustrate the way power can be exercised in supply-chain arrangements that preserve the status quo. The first struggle relates to softwood; the second to nail plate.

Structural softwood is produced in Australia by approximately six to eight companies, and there are eight to 10 softwood importers of significance (Participant T9). These are all reasonably sized business turning over between \$100 and \$120 million. However:

With \$100 and \$120 million turnover in business, these are reasonably sized sophisticated businesses. One of the reasons that [an Australian timber manufacturer] was originally trying to go into the prefabrication area was to have more degrees of freedom. They were threatened by their customers, who said that if they continued to do this, they wouldn't buy as much timber. The supply chain [downstream] is locked in on you by one of the actor groups. (Participant T9)

Another value chain lock-in relates to the role played by nail-plate companies such as Pryda, Multinail and MiTek. Setting up a frame and truss company is a low capital business, requiring truss and wall panel machinery, software, training and finance. The arrangement set up between the nail plate company and the frame and truss company can be financially '*on good terms*'. However, the arrangement also means that a frame and truss company cannot shift to another nail-plate company. Participant T9 explained that the manufacturer '*effectively becomes trapped in that ecosystem*':

Frame and truss companies are basically jobbing shops. Every frame and truss is effectively different. You can only make them one at a time, or if you've got two lines, two at a time. There is no manufacturing efficiency, no economies of scale. There's no standard truss produced in Australia ... In some ways it's a form of sharecropping; they are a captured value chain. One of the few things that these small companies can change about their business is their timber supply. Their role might have 100 per cent loyalty to a nail-plate company, but they do not have any significant loyalty, or less loyalty, to a timber company, and will shop around. (Participant T9)

Overall, relationships in the timber supply chain are structured around a set of interests that militate against industry development and innovation in the use of timber in the HCl industry:

If you are a timber company, and to some extent through the wholesale chain as well, the timber industry is basically trapped by its customers. Even though they are much bigger in size and sophistication, they are not controllers of their destiny. (Participant T9)

4.4.3 Timber industry innovation

Two areas of timber industry innovation show how industry supply chains are resistant to change. First is the difficulty in getting timber to be used in mid-rise, multi-unit apartment housing structures. Mid-rise, multi-unit housing in the MUACTI industry has traditionally been built by constructing buildings with reinforced concrete columns and floors. They can be built with timber, but this innovation has largely not been adopted. Second, there is considerable scope for reducing waste and increasing the flow of materials through the timber supply chain by greater use of Industry 4.0 digital technologies.

Timber and multi-unit apartments

In 2016, the use of timber to build MUACTI mid-rise residential apartment buildings was allowed following the incorporation of a 'deemed-to-satisfy provision' in the NCC, allowing for residential apartment buildings up to 25 metres in height (8–9 storeys). Two existing timber buildings informed the development of the NCC deemed-to-satisfy provisions: Forte, built by Lendlease; and The Green, built by Fraser's. The factor that enabled their acceptance was responding to fire risks '*by encasing [timber] in fire-resistant plasterboard*' (Participant T9).

Two types of timber construction can be used to construct multi-unit apartments: stick building and EWPs. The stick-built technology extends the technology used in the residential house construction industry, which uses timber-framed walls, timber floors and roof trusses. In multi-unit construction, the frames and floors are stacked on top of each other. The EWPs are bespoke products that meet specified design requirements and structural standards. However, the adoption of these two timber technologies in the MUACTI industry has largely stalled.

In the case of the stick-built industry, supporters have largely failed to generate interest from within the HCl to extend their operations into a new type of construction using well-established stick-built technology and skills:

Despite all the effort ... there's still no frame and truss company in Australia that wants to supply the non-detached market. And particularly to go through the market cycles that we've had, even though they would have had the capacity to do it anyway. So, effectively after six years and since the introduction of the deem-to-satisfy provisions, we've failed to deliver lightweight multi-residential construction. (Participant T9)

The take-up of EWPs in the MUACTI industry has also failed, despite it being used in university, corporate and state government buildings, as well as in institutional residential buildings such as student accommodation. Developers in the MUACTI industry, with a few exceptions, have not switched from designing and building reinforced concrete-framed buildings to the unfamiliar EWP technology manufactured and prefabricated offsite factories.

The FWPA Wood Solutions training project and the production of Technical Design Guides has not convinced the MUACTI developers, their finance sources, design consultants and builders to initiate and procure timber multi-unit apartment buildings. In this context, there is scope for reviewing the way these actor groups identify and assess risks that could arise in a transition from reinforced concrete to timber as the main structural material in multi-unit apartment buildings.

Industry 4.0 digital technologies

Digital technologies can support information-sharing and improve coordination along the supply chain, which is dominated by SMEs with no R&D capacity and limited access to capital. Digital technologies have the potential to increase efficiency and reduce waste. This has led to a FWPA project that has made progress in introducing digital technologies to some parts of the industry. An example is the use of digital technology to scan logs going through sawmills: FWPA funded the research that enabled all the sawmills to benefit from upgrading their scanners. This upgrade, coupled with the right software, supported better analysis of log volumes and enabled optimal cutting of timber to different sizes and lengths. This type of innovation is in everyone's interest because they are all paying for the material.

However, a problem still remains, as the downstream sawn timber users are not digitally connected to the sawmillers. This means that downstream user data about the lengths they cut when making up wall frames and trusses is not transmitted back to the sawmillers. The sawmillers have no data to make decisions about the lengths that could significantly reduce waste created by downstream users. Participant T1 describes the problem:

Because he's busy buying a 6-metre length, he cuts it down to a 1.8 metre, and he ends up with 30 per cent waste. Whereas if his cutting patterns were fed back to the sawmiller, the sawmiller could go, 'Great, I can punch bloody ten 1.8 metre lengths out of these logs, and get more productivity.' (Participant T1)

Because of this failure to digitally join up firms along the supply chain, the levels of waste increase. As Participant T1 says: '*They can't get enough material, and they're wasting 10 or 15 per cent of it because the sizes don't fit what they have to cut.*'

Digital technologies can also support information-sharing along the supply chain, improve coordination and reduce waste. The idea of supply-chain integration could even be extended by pooling data so that it can be used up and down the supply chain by growers, sawmillers, distributors, wholesalers and manufacturers. Participant T1 sums up the situation: '*We need to grow more trees, but that's going to take 20–30 years ... but something we can do in the short term is improve productivity.*'

4.4.4 Timber industry institutional challenges

There are two stand-out institutional challenges facing the Australian timber industry and supplying timber for future use in residential housing. They are:

- the continuing reliance on imported timber, and a forecast increase in this reliance
- the failure to systematically consider how the enormous stocks of timber already layered into the existing residential housing stock will be reused as this stock is progressively renewed.

Reliance on imported timber

Australia relies on timber imports. The long-term annual average of timber imports has been 20 per cent of total supply by volume, and the gap is forecast to reach 40 per cent by 2050 (Woods and Houghton 2022: 6). There are two reasons for this reliance on imports. First, the increased protection of native forests has resulted in a decline in hardwood timber. Second, plantation timber policy has led to growth, but it is insufficient. Jenkin (2018: 10) sums up the history of plantation timber production:

Farm forestry has been a grand experiment promoting commercially un-proven species to be planted and managed in a commercially un-proven manner in areas lacking a market for the target log outcomes.

In this context, Participant T9 argues for '*providing an incentive to increase the amount of commercial wood production in Australia through planting more trees ... a properly planned plantation policy.*' Participant T9 sees the need for urgency because timber is competing with steel:

We've only got probably got 10 to 15 years left as a competitive advantage. As soon as you have recycled steel that is being produced with renewable energy, the embodied energy of steel will probably be as good or better than wood products. (Participant T9)

There is broad recognition for the need to reformulate plantation policy. The history, management, policy settings and prospects of plantations have been well researched (Jenkin 2018; Jenkin, Keenan et al. 2019; Standing Committee on Agriculture and Water Resources 2021; Whittle, Lock et al. 2019) and provide the basis for stakeholder engagement and a process for reformulation.

Waste and reuse

Existing buildings, particularly housing built over a very long period of time, contain very large quantities of timber. As these buildings reach the end of life, they are typically demolished. The question in this era where the conservation of building materials is becoming a priority is: how should recycled timber be treated? Data from the states and territories indicates that in 2016–17 nearly 2.4 million tonnes (2,369,680 t) of timber waste was generated. It is estimated that the construction and demolition sector was responsible for 26 per cent, and the commerce and industry sector 64 per cent (Shooshtarian, Maqsood et al. 2019: 24).

Currently there is no regulation of used timber. It is simply assumed to be waste and it is one form of waste among many that is covered by the same legislation as general waste. Nor is there a commonly accepted practice that leads to the systematic conservation and reuse of timber. Nevertheless, there is a market for recycled timber. However, it is a small market that tends to focus on highly valued larger pieces of timber that are retrieved and reused for furniture and featured in new constructions. A common practice is demolition and disposal of the timber as waste. Participant T1 graphically describes what usually happens:

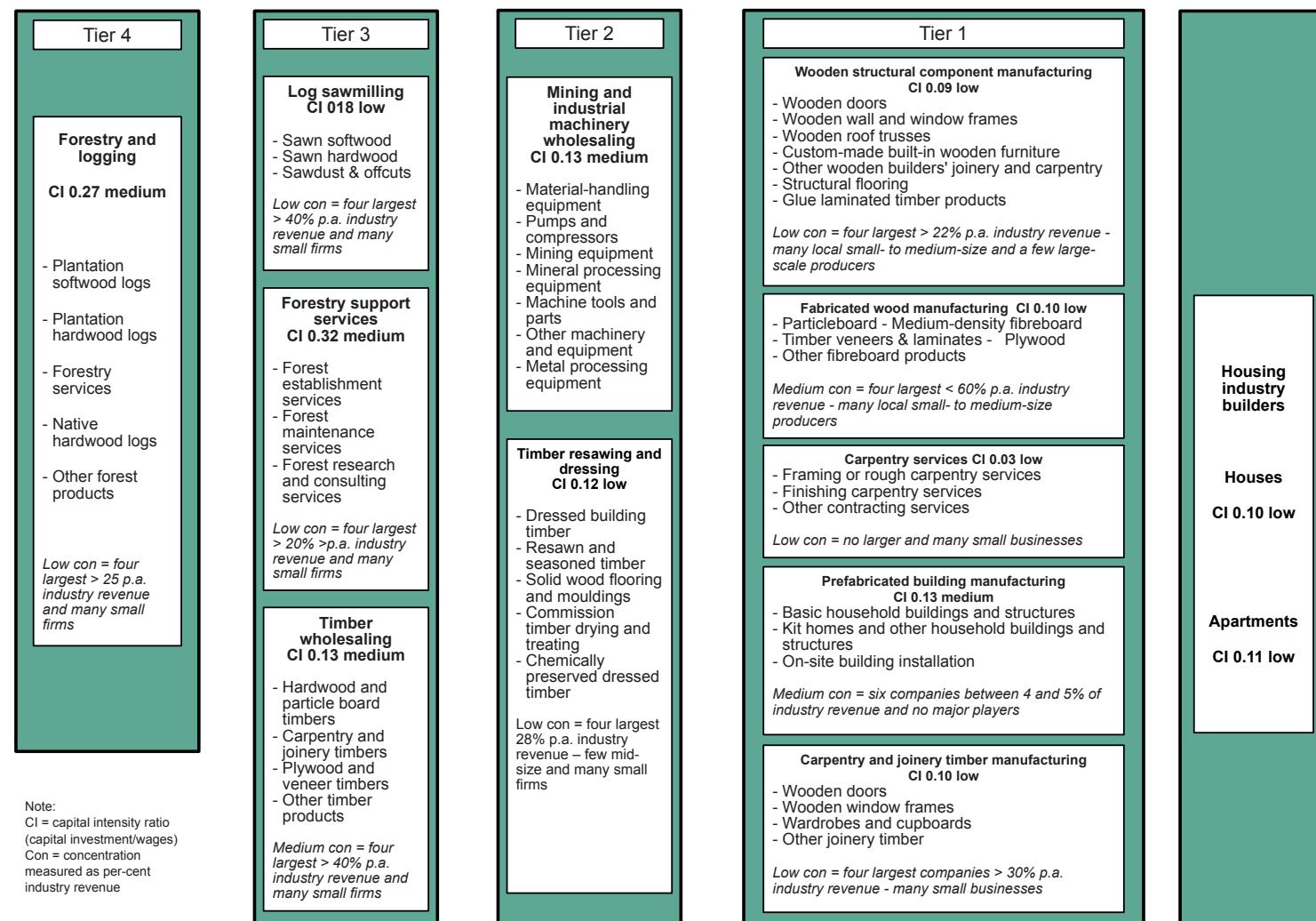
That's the reuse challenge, because any reuse that sort of appeals to people looking at circular economy is really boutique [...] But that would be 1 per cent of what happens, because these houses that are getting demolished, I looked at some data the other day, that 16,000 houses were knocked over last year in Australia, most of them would just be bowled over, put in the back of a truck and probably 90 per cent of it ends up in landfill because no one bothers to even try and strip the timber out of it. (Participant T1)

For most actors in the demolition and the housing industry, recycled timber is regarded as 'waste' as opposed to 'resource', as it is perceived as having little to no value:

It's like everything in our industry. Everyone's a tightwad so they don't pay for that, they say, 'Oh, we're doing you a favour by getting rid of your waste,' so they aren't paying the frame and truss guy for his waste, which is sort of crazy because it's obviously got value. This is always the great dispute in our industry: who makes the money? Where does the value sit? And everyone always figures it's the other bloke who's getting the money rather than them. (Participant T1)

Another challenge with reuse is the potential toxicity of treated timber products. As Participant T1 put it: *'How do we deal with treated products within that mix? Because you can't put treated products through the same process, because the chemicals can be toxic'* (Participant T1).

Figure 16: Timber industry supply chain



Source: Authors based on IBISWorld industry reports.

4.5 Policy development implications for building materials supply chains

This section has presented case-study analyses of the institutional arrangements that produce concrete, steel and timber building materials that flow into and out of the residential housing system. Builders in both building construction industries orchestrate these material flows onto building sites and into dwellings. However, they do this within a context where many other actor groups—such as built-environment professionals, finance institutions, regulators, developers, distributors, manufacturers and purchasers—all contribute to establishing the ‘rules of the game’.

Until now, the carbon embodied in the materials flowing into and out of the housing system has not been a concern of any of these actor groups. This is the context for the development of a CE policy framework that can guide some actors to insist that recognising and reducing embodied carbon be incorporated into the ‘rules of the game’.

Three areas of policy development are proposed that could assist in reforming the ‘rules of the game’ for the use and reuse of building materials in the residential housing sector:

- learning about carbon in building materials
- regulation
- supply chains and industry policy.

4.5.1 Learning about carbon in building materials

The idea that carbon can be embodied in building materials is a new concept for most people involved in the residential housing system—employees, contractors and subcontractors, consultants, professionals and regulators. Education and training systems could potentially provide the means for increasing the knowledge and understanding of carbon in building materials by those working in the residential housing system. The higher education, TAFE and professional development systems could all make a contribution. Initial steps that could be taken in developing a policy and program development initiative are outlined below.

- Find a suitable high-profile government agency or civil society organisation to prepare a discussion and consultation paper on learning about carbon in building materials through higher education, TAFE and professional development.
- Conduct a national consultation with industry intermediary organisations—such as industry associations, professional associations and civil society organisations—universities with built-environment programs, TAFE colleges with built-environment trade programs.
- Present the report with recommendations for a national program to support learning about carbon in building materials to federal, state and territory governments, seeking their resourcing and support to include this form of learning into their climate change mitigation strategies.

4.5.2 Regulating for low carbon

The NCC is a performance-based code that sets minimum levels for the safety, health, amenity, accessibility and sustainability of buildings. The Australian Building Control Board (ABCB) acts on behalf of the federal, state and territory governments to produce and revise the NCC. The ABCB could be required to expand the scope of its sustainability regulation to support the decarbonisation of the housing system by regulating to lower the embodied carbon in material flows into housing, along with the reuse of CDW materials from the housing system.

The extended regulatory regime should be supported by a simple-to-use digital recording system that records the flow of materials into the housing system. This should be based on a system that reads bills of quantity and requires manufacturers to generate EPDs for all materials. This system should be designed so that there is national monitoring of the stocks and flows of materials in the housing system, while also supporting regulators at the local, regional and state or territory levels.

4.5.3 Supply chains and industry policy

Building-material supply chains are complex. They involve different actors that are often uncoordinated and have conflicting interests, including manufacturers, distributors, retailers, regulators, professional consultants, contractors and subcontractors. Many of these actors, in addition to participating in complex supply chains, are also members of or are affiliated with an intermediary organisation such as an industry or professional association. For example, a sheet-metal product manufacturer might belong to the Metal Roofing and Cladding Association. Further, the CEO might be a member of Engineers Australia.

These multiple forms of affiliation, including firm, industry and profession, provide the basis for formalising consultative arrangements for supply chains that could support collaborative supply-chain decarbonisation planning and implementation. For example, it would be possible to identify the actors that are involved in the manufacturing, specifying, delivery and installation of concrete to residential housing projects. On this basis those involved in the relevant intermediary organisations such as the CCAA, Concrete Institute of Australia, Steel Reinforcement Institute of Australia, HIA, MBA, Engineers Australia, Australian Institute of Quantity Surveyors and AIB could be brought together. These temporary network organisations could be established as housing-industry supply-chain councils.

The industry supply-chain councils would be resourced by two federal ministerial agencies in the areas of climate change mitigation and industry development. In line with suitable terms of reference, they would be supported to identify the constraints and opportunities for CE, decarbonisation and industry development. The processes they could use include research and consultation papers, proposals for industry/supply chain support programs, regulatory reform, research projects and areas for de-risking investment through the Clean Energy Finance Corporation.

5. Policy recommendations

Section 5.1 summarises the key findings against the guiding project research questions. Section 5.2 connects the findings with the strategy elaborated as part of the Inquiry overarching project.

5.1 Summary of research findings

Who are the key institutional actors in the supply chain supplying materials for use in the Australian residential housing system?

The institutional perspective reveals how industry fragmentation continues to shape the flow of building materials in housing construction. Builders in the housing industry draw materials for house and multi-unit apartment construction from many supply chains, and draw products and services from at least 27 industries. Some building materials supply chains are dominated by oligopolistic building materials manufacturers, while others are more fragmented, with a larger presence of SMEs. There are also innovators and risk takers seeking to change materials design, production, distribution, disposal and reuse. There are various opportunities and constraints for CE innovation both within oligopolistic supply-chain arrangements and smaller innovative risk-taking companies. All key institutional actors in the supply chain will need to change if there is to be systematic and deep reduction, reuse, recycling and recovery of resources.

What supply-side/demand-side drivers can increase the contribution that materials production and distribution can make to a CE?

The research established that the CE concept is not an embedded or well-understood concept in the material supply chain and housing industries. However, a number of drivers were identified that have the potential to help shift the framing and conduct of supply chain industries so that they could become more familiar with CE concepts and practices. These drivers include:

- financially incentivising improved design, including design for deconstruction
- construction and end-of-life practices, including end-of-life stewardship responsibilities
- ensuring that large-scale stockpiling of used materials is practical and affordable
- ensuring that NCC regulations and local planning approvals are developed and implemented so that regulation supports CE.

The efficacy and continued development of drivers can be supported by the improved recording of the flow and composition of materials through the use of material passports into and out of the residential housing system.

What are the needs and opportunities for training and Australian jobs in the creation of the materials supply chain within a developing CE?

The research finds that there is little understanding or interest in how to introduce and make CE changes, and that there will be a need for significant (re)training of key industry stakeholders. An example was seen in The Cape case study in Section 3.2, where stakeholder training on new measures was provided in how to prevent thermal bridging, and how to seal buildings. The two case studies highlighted the benefits of contractors and subcontractors collaborating so that everyone improves. This approach is different to much of the industry, where businesses compete and protect their IP. Within the industry more broadly, there are few opportunities to learn about CE practices such as disassembly and materials reuse. For those who do have knowledge and experience in CE, there will be opportunities to work in this area as demand for expertise grows.

What are the key innovation challenges and opportunities from Industry 4.0 and the use of materials in the Australian residential housing system?

Material stocks used by housing industry, dominated by heavyweight materials such as brick and concrete, continues to increase. Development of databases and the capacity to use the data will require significant innovation. A starting point is to ensure that the data is captured through the required submission of ABDs and digital passports. These measures provide a framework for tracking materials and product use over time and will extend the practices of deconstruction, reuse and recycling. They can also assist in understanding the cost of CE practices, and how they can be factored into the economics of new buildings and their maintenance. Also, these measures can assist in costing the constraints flowing from the lack of factory-based offsite manufacturing where CE systems and practices are more easily established.

What are the challenges and opportunities—financial, fiscal, regulatory and policy—for material use resulting in more sustainable design and build outcomes?

The challenge for the housing sector is to develop strategies to decarbonise the flow of materials into the housing stock, increase material reuse and reduce the use of new materials. CE principles are best put in place at the design phase, which can be difficult given the lack of expertise. The recovery and reuse of building materials is also difficult in the absence of regulation, underpricing of landfill, the absence of markets, poor waste-stream data collection, and designs that do not support material end-of-life recovery. There is some reuse of materials, principally concrete and steel, where there is stewardship and markets. However, timber reuse is limited to niche or boutique initiatives, or is downcycled into mulch or fencing. The costs of cleaning up timber by removing nails and its compliance with standards are issues that make reuse problematic. Similarly, kitchen and plumbing supplies are rarely reused or recycled as high-quality recovery is compromised when deconstruction is not designed for at the outset. Brick recycling is labour intensive, as bricks require cleaning prior to reuse, and transport is expensive.

5.2 Project recommendations towards CE housing

Important policy issues and policy responses were identified during the course of the research presented in the Sections 1–4, which focussed on:

- the structure of the housing industry, which is split between HCI detached housing and MUATCI multi-unit apartment housing
- the availability of data that can be used to map and analyse the flow of materials into and out of the housing system
- design and onsite decisions about material choice and material reuse for low-rise and multi-unit apartment housing construction
- the institutional arrangements of manufactured material supply chains that supply materials to housing industry builders.

The following areas for policy development were identified, and preliminary ideas for their further development are outlined.

- **Materials data collection and analysis:** The research identified significant gaps in data necessary for understanding the flow of materials used in the construction of housing, materials already in the housing system, construction and disassembly waste, and reuse. The Australian Housing Data Portal established by the CSIRO has made considerable progress in the development of a data system, but better builder reporting is required. Future initiatives should include the digital recording of material flows through ABDs and material passports, supporting stock in-use and materials tracking over the lifespan of dwellings. Data should also support analysis of materials used at regional and local scales.
- **Incentivising disassembly and reuse:** It is difficult for building-industry stakeholders to economically justify disassembly and reuse. Policy development should focus on incentivising disassembly for material reuse, as well as encouraging other ways to reduce embodied energy through material selection and the use of local products that require less transportation. Creating reuse markets within Australia is important, but given global supply chains it is likely that these markets will connect with international markets. Ensuring that local building-industry stakeholders are not penalised by markets that do not value waste may require consideration of border-adjustment regulation.
- **Regulation for low carbon:** The NCC is a performance-based code that sets minimum levels for the safety, health, amenity, accessibility and sustainability of buildings. Future NCC regulation could expand the scope of sustainability regulation to support housing-system decarbonisation. The focus to date has been on reducing operational carbon emissions rather than whole-of-life carbon emissions. NCC regulations could lower the embodied carbon in material flows and support the reuse of CDW materials. This extended regulatory regime would be supported by simple-to-use digital recording systems for recording material flows. Most recycling and reuse regulations focus on end-of-pipe solutions. Regulations should support reuse, rethink, repurpose or remanufacture.
- **Tilting investment flows:** Policy makers can shape investment flows in ways that support decarbonisation of material industries. This form of investment, accompanied by regulation, can support the decarbonisation of materials manufacturing and stimulate demand for recycled materials. Strategic use of public procurement is a complementary form of support. The use of taxation policy can also guide optimisation of resource use in material life cycles, including raw materials resource taxes, tax relief on reuse and repair, and carbon credits to incentivise reduced emissions.
- **Building capacity:** Expanding the pool of people with a knowledge of CE education, training and skill development is a high priority. This can be done through curriculum development for use in universities and TAFEs, and in professional development in-service training that presents CE and embodied carbon concepts in the built environment. This education and training program would focus on topics such as materials manufacturing, digital recording of material flows, material supply chains, materials innovation, construction, maintenance and deconstruction processes, building-industry institutional arrangements and emissions reduction policy.
- **Supply-chain decarbonisation planning:** Building-materials supply chains are complex. They involve different actors that are often uncoordinated and have conflicting interests, including manufacturers, distributors, retailers, regulators, professional consultants, contractors, subcontractors and social movement organisations. There is a case for establishing housing-industry supply-chain councils. Council members would be drawn from industry and professional associations and civil society social movement organisations, including relevant unions. Each council, supported by a federal government industry agency, would support a deliberative process that aims at developing a supply-chain decarbonisation plan.

5.3 Final remarks

It is clear from the research that support from the residential housing industry for the integration of CE into the residential housing material supply chains is limited. A significant government policy effort and willingness by the industry to support a transition towards CE ways of working will be required.

The public policy focus to date has been largely about regulating the industry to improve the energy efficiency of new houses and apartments. Implementing a higher standard has been a long, drawn-out process, where the housing industry has sought to slow down the implementation of higher standards.

A move to a CE-driven housing industry will require substantial whole of industry change, including the housing industry and its supply chains. However, there is a new imperative that will flow from the new commitment by the Australian Government to legislate higher emission-reduction targets.

The Intergovernmental Panel on Climate Change (IPCC) has signalled that developed industrialised countries will have to extend their emission abatements beyond switching to renewable electrical energy generation and electrifying motor vehicle transport. The IPCC (2022: 11-6) has observed that until recently 'industry has so far largely been sheltered from the impacts of climate policy and carbon pricing due to concerns for competitiveness and carbon leakage'.

The IPCC has now made it clear that industry faces a challenge, and it is worth quoting in conclusion:

Net-zero CO₂ emissions from the industrial sector are challenging but possible. Reducing industry emissions will entail coordinated action throughout value chains to promote all mitigation options, including demand management, energy and materials efficiency, circular material flows, as well as abatement technologies and transformational changes in production processes. (IPCC 2022: SPM-38)

It is important to remember that the housing industry is included in the IPCC definition of industry.

References

- ABCB (2023) General User, NCC, accessed 20 April 2023, <https://ncc.abcb.gov.au/homeowners>.
- ABS (2006) Australian and New Zealand Standard Industrial Classification (ANZSIC), ABS, Canberra.
- ABS (2021a) National, state & territory level dwelling demolition approvals, accessed 19 July 2022, <https://www.abs.gov.au/articles/national-state-territory-level-dwelling-demolition-approvals#data-download>.
- ABS (2021b) Building activity, Australia, accessed 6 June 2022, www.abs.gov.au/statistics/industry/building-and-construction/building-activity-australia/latest-release
- ABS (2021c) Functional classification of buildings, ABS, Canberra, accessed 23 February 2023, www.abs.gov.au/statistics/classifications/functional-classification-buildings/latest-release.
- ABS (2022a) 50 years of capital city population change, ABS, Canberra, accessed 22 February 2023, www.abs.gov.au/articles/50-years-capital-city-population-change.
- ABS (2022b) Building Activity Australia, Number of dwelling unit completions by sector, Australia, Canberra, accessed 27 April 2023, [https://www.abs.gov.au/statistics/industry/building-and-construction/building-activity-australia/latest-release](http://www.abs.gov.au/statistics/industry/building-and-construction/building-activity-australia/latest-release).
- ABS (2023), 8752.0 Building Activity Australia, Table 37, Number of dwelling unit completions by sector, Australia.
- ACCC (2019) 'Action against BlueScope for alleged cartel conduct', accessed 21 April 2023, <https://www.accc.gov.au/media-release/action-against-bluescope-for-alleged-cartel-conduct>.
- ACCC (2022) Cartels, Australian Competition and Consumer Commission, Canberra, accessed 28 April 2023, [https://www.accc.gov.au/business/competition-and-exemptions/cartels](http://www.accc.gov.au/business/competition-and-exemptions/cartels).
- Adams, M., Burrows, V. and Richardson, S. (2019) *Bringing embodied carbon upfront: coordinated action for the building and construction sector to tackle embodied carbon*, World Green Building Council, accessed 1 May 2023, <https://worldgbc.org/article/bringing-embodied-carbon-upfront/>.
- AIA (2022) Climate change and the architectural profession, Australian Institute of Architects, accessed 1 June 2022, <https://www.architecture.com.au/archives/reading-architecture/climate-change-and-the-architectural-profession>.
- Al Nuaimi, E., Al Neyadi, H., Mohamed, N. and Al-Jaroodi, J. (2015) 'Applications of big data to smart cities', *Journal of Internet Services and Applications*, vol. 6, no. 1, doi:10.1186/s13174-015-0041-5.
- Arehart, J.H., Pomponi, F., D'Amico, B. and Srubar III, W.V. (2022) 'Structural material demand and associated embodied carbon emissions of the United States building stock: 2020–2100', *Resources, Conservation and Recycling*, vol. 186, art. 106583. doi:10.1016/j.resconrec.2022.106583.
- Asadullah, A. (2018) *Digital platforms: a review and future directions*, Pacific Asia Conference on Information Systems (PACIS), Japan.
- Augiseau, V. and Barles, S. (2017) 'Studying construction materials flows and stock: a review', *Resources, Conservation and Recycling*, no. 123: 153–164, doi:10.1016/j.resconrec.2016.09.002.
- Australian Construction Insights (ACI) (2018) *Framing material use in residential construction: an investigation of the factors influencing framing material choice in residential building*, prepared for Forest Wood Products Australia, accessed 1 May 2023, https://fwpwa.com.au/wp-content/uploads/2018/12/ACI_Structural_framing_materials_used_in_residential_building_Final_3Dec2018.pdf.

- Australian Government (2019) *The National Waste Policy Action Plan 2019*, Australian Government, state and territory governments and the Australian Local Government Association, Department of Climate Change, Energy, the Environment and Water, Canberra, accessed 1 May 2023, <https://www.agriculture.gov.au/sites/default/files/documents/national-waste-policy-action-plan-2019.pdf>.
- Australian Labor Party (2021) *Powering Australia: Labor's plan to create jobs, cut power bills and reduce emissions by boosting renewable energy*, Australian Labor Party (Canberra), accessed 1 May 2023, <https://www.alp.org.au/policies/powering-australia>.
- Baikie, V. (2021a) *Architectural services in Australia*, IBISWorld.
- Baikie, V. (2021b) *Iron smelting and steel manufacturing in Australia*, IBISWorld.
- Baron, R. (2016) *The role of public procurement in low-carbon innovation*, OECD, Paris, accessed 1 May 2023, <https://www.oecd.org/sd-roundtable/papersandpublications/The%20Role%20of%20Public%20Procurement%20in%20Low-carbon%20Innovation.pdf>.
- Battelle Memorial Institute (2002) *Toward a sustainable cement industry*, Battelle Memorial Institute, accessed 1 May 2023, <https://www.wbcsd.org/Sector-Projects/Cement-Sustainability-Initiative/Resources/Toward-a-Sustainable-Cement-Industry>.
- Berry, S. and Marker, T. (2015) 'Residential energy efficiency standards in Australia: where to next?', *Energy Efficiency*, vol. 8: 963–974. doi:[10.1007/s12053-015-9336-4](https://doi.org/10.1007/s12053-015-9336-4).
- Beyond Zero Emissions (2017) *Zero carbon industry plan: rethinking cement*, BZE, Melbourne, accessed 1 May 2023, <https://bze.org.au/wp-content/uploads/2020/12/rethinking-cement-bze-report-2017.pdf>
- Bhatt, M., Suchan, J., Schultz, C., Kondyli, V., & Goyal, S. (2016) 'Artificial intelligence for predictive and evidence based architecture design', *Proceedings of the AAAI Conference on Artificial Intelligence*, vol. 30, no. 1. doi:[10.1609/aaai.v30i1.9850](https://doi.org/10.1609/aaai.v30i1.9850).
- Black, J. (2002) 'Critical reflections on regulation', *Australian Journal of Legal Philosophy*, no. 27: 1–35.
- BlueScope (2021a) *Climate action report*, BlueScope, accessed 1 May 2023, <https://s3-ap-southeast-2.amazonaws.com/bluescope-corporate-umbraco-media/media/3313/bluescope-climate-action-report-2021.pdf>.
- BlueScope (2021b) *Sustainability report 2020/21*, BlueScope, accessed 1 May 2023, <https://www.bluescope.com/bluescope-news/2021/09/bluescope-sustainability-report-fy2021/>.
- BlueScope Steel Limited (2021) *BlueScope Investor Day: Day 2*, accessed 1 May 2023, <https://www.bluescope.com/investors/presentations/2021/09/bluescope-investor-briefing/?page=1&year=2021>.
- Böhme, T., Escribano, A., Heffernan, E.E. and Beazley, S. (2018) 'Causes and mitigation for declining productivity in the Australian mid-rise residential construction sector', *Built Environment Project and Asset Management*, vol. 8, no. 3: 253–266, doi:[10.1108/bepam-10-2017-0097](https://doi.org/10.1108/bepam-10-2017-0097).
- Boral Limited (2020) *Boral review and sustainability report 2020*, accessed 1 May 2023, <https://www.listcorp.com/asx/bld/boral-limited/news/2020-boral-review-and-sustainability-report-2372539.html>.
- Bosch, G. and Philips, P. (2003) 'Introduction', in G. Bosch and P. Philips (eds), *Building Chaos : An International Comparison of Deregulation in the Construction Industry*. Routledge, London.
- BPIE (2021) *Addressing the hidden emissions in buildings: Status quo, gaps, and recommendations for environmental product declarations and whole-life carbon*, Buildings Performance Institute Europe, Belgium/Germany, accessed 1 May 2023, <https://www.bpie.eu/publication/addressing-the-hidden-emissions-in-buildings-status-quo-gaps-and-recommendations-for-environmental-product-declarations-and-whole-life-carbon/>.
- Bressanelli, G., Perona, M. and Saccani, N. (2018) 'Challenges in supply chain redesign for the circular economy: a literature review and a multiple case study', *International Journal of Production Research*, vol. 57, no. 23: 7395–7422, doi:[10.1080/00207543.2018.1542176](https://doi.org/10.1080/00207543.2018.1542176).
- Brickworks Limited (2020) *Brickworks sustainability report*, Sydney, accessed 1 May 2023, <https://investors.brickworks.com.au/wp-content/uploads/2020/12/Sustainability-Report-Oct2020.pdf>.
- Bringezu, S. and Moriguchi, Y. (2002) 'Material flow analysis', in R.U. Ayres and L. Ayres (eds), *A Handbook of Industrial Ecology*, Edward Elgar, Cheltenham: 79–90.
- Brunner, P.H. and Rechberger, H. (2016) *Handbook of Material Flow Analysis: For Environmental, Resource, and Waste Engineers*, CRC Press.

- Burger, M., Stavropoulos, S., Ramkumar, S., Dufourmont, J. and van Oort, F. (2019) 'The heterogeneous skill-base of circular economy employment', *Research Policy*, vol. 48, no. 1: 248–261. [doi:10.1016/j.respol.2018.08.015](https://doi.org/10.1016/j.respol.2018.08.015).
- Campbell, A. (2019) 'Mass timber in the circular economy: paradigm in practice?' *Proceedings of the Institution of Civil Engineers. Engineering Sustainability*, vol. 172, no. 3: 141–152. [doi:10.1680/jensu.17.00069](https://doi.org/10.1680/jensu.17.00069).
- Carvalho, L.F., Jorge, L.F.C. and Jerónimo, R. (2020) 'Plug-and-play multistory mass timber buildings: achievements and potentials', *Journal of Architectural Engineering*, vol. 26, no. 2. [doi:10.1061/\(ASCE\)AE.1943-5568.0000394](https://doi.org/10.1061/(ASCE)AE.1943-5568.0000394).
- CCAA (2021) 'Key pathways to net zero for Australian cement and concrete identified', Cement, Concrete and Aggregates Australia, Sydney, accessed 1 May 2023, [https://smartcretecrc.com.au/key-pathways-to-netzero-for-australian-cement-and-concrete-identified/](https://smartcretecrc.com.au/key-pathways-to-net-zero-for-australian-cement-and-concrete-identified/).
- Çetin, S., De Wolf, C. and Bocken, N. (2021) 'Circular digital built environment: an emerging framework', *Sustainability*, vol. 13, no. 11. [doi:10.3390/su13116348](https://doi.org/10.3390/su13116348).
- Chang, K.T. (2016) 'Geographic information system' in D. Richardson, N. Castree, M.F. Goodchild, A. Kobayashi, W. Liu and R.A. Marston (eds), *International Encyclopedia of Geography: People, the Earth, Environment and Technology*, Wiley, <https://onlinelibrary.wiley.com/doi/10.1002/9781118786352.wbieg0152>.
- Charef, R. and S. Emmitt (2021) 'Uses of building information modelling for overcoming barriers to a circular economy', *Journal of Cleaner Production*, no. 285, [doi:10.1016/j.jclepro.2020.124854](https://doi.org/10.1016/j.jclepro.2020.124854).
- Churkina, G., Organschi, A., Reyer, C.P.O., Ruff, A., Vinke, K., Liu, Z., Reck, B.K., Graedel, T.E. and Schellnhuber, H.J. (2020) 'Buildings as a global carbon sink', *Nature Sustainability*, vol. 3, no. 4: 269–276. [doi:10.1038/s41893-019-0462-4](https://doi.org/10.1038/s41893-019-0462-4).
- Circle Economy (2019) *The Circularity Gap report 2019*, The Circularity Gap Reporting Initiative, The Platform for Accelerating the Circular Economy (PACE), accessed 1 May 2023, https://circularconomy.europa.eu/platform/sites/default/files/circularity_gap_report_2019.pdf.
- Clean Energy Regulator (2022) 'What data is published and why', National Greenhouse and Energy Reporting, accessed 1 May 2023, <https://www.cleanenergyregulator.gov.au/NGER/National%20greenhouse%20and%20energy%20reporting%20data/What-data-is-published-and-why>.
- Climate Works Australia (2020) *Australian Industry Energy Transitions Initiative*, Australian Industry ETI, <https://energytransitioninitiative.org/>.
- Coffee, N.T., Lange, J. and Baker, E. (2016) 'Visualising 30 years of population density change in Australia's major capital cities', *Australian Geographer*, vol. 47, no. 4: 511–525, [doi:10.1080/00049182.2016.1220901](https://doi.org/10.1080/00049182.2016.1220901).
- Colacino, P. (2018) 'Keeping our cities liveable as they grow', *National Growth Areas Alliance Congress 2018*, Sydney, 19 November 2018, <https://www.infrastructureaustralia.gov.au/listing/speech/keeping-our-cities-liveable-they-grow>.
- Condeixa, K., Haddad, A. and Boer, D., 2017. 'Material flow analysis of the residential building stock at the city of Rio de Janeiro', *Journal of Cleaner Production*, no. 149: 1249–1267, [doi:10.1016/j.jclepro.2017.02.080](https://doi.org/10.1016/j.jclepro.2017.02.080).
- Crabtree, L., and D. Hes (2009) 'Sustainability uptake in housing in metropolitan australia: an institutional problem, not a technological one', *Housing Studies*, vol. 24, no. 2: 203–224, [doi:10.1080/02673030802704337](https://doi.org/10.1080/02673030802704337).
- Crawford, R.H., Stephan, A. and Prudeaux, F., 2019. *Environmental Performance in Construction (EPiC) Database*. [doi:10.26188/5dd4cd6ad1e2e](https://doi.org/10.26188/5dd4cd6ad1e2e).
- Crommelin, L., Sian T., Hazel E., Loosemore, M., Yang, H., Buckle, C. and Randolph, B. (2021) *Cracks in the compact city: tackling defects in multi-unit strata housing*. University of Technology Sydney and UNSW City Futures Research Centre, https://cityfutures.ada.unsw.edu.au/documents/670/Defects_final_report_for_publication_HSGP9LW.pdf.
- Crowther (2000) 'Building deconstruction in Australia', in Kibert, C. J., Chini, A. R. and Rinker Sr, M. Overview of *Deconstruction in Selected Countries*, CIB, International Council for Research and Innovation in Building Construction Task Group 39: Deconstruction Center for Construction and Environment, accessed 1 May 2023, <http://s14.cfaa.ufl.edu/centers/sustainable/>.
- CSR Limited (2019) *Sustainability Report 2019*, accessed 1 May 2023, https://www csr com au/-/media/corporate/files/sustainability-reports/csr_sustainability_2019 pdf?la=en&hash=5B47D402325162F841D72A38D3FC3DC4CA9FB87B.
- Daehn, K.E., Cabrera Serrenho, A. and Allwood, J.M. (2017) 'How will copper contamination constrain future global steel recycling?', *Environmental Science & Technology*, vol. 51, no. 11: 6599–6606, <https://www.ncbi.nlm.nih.gov/pubmed/28445647>.
- DAFF (2008) *Australian forest profiles: plantations*, Bureau of Rural Science, accessed 1 May 2023, <https://www.agriculture.gov.au/abares/forestsaustralia/australias-forests/profiles>.

- Dalton, T., Horne, R., Chhetri, P., and Corcoran, J. (2013) *Understanding the patterns, characteristics and trends in the housing sector labour force*, AHURI Final Report No. 208, Australian Housing and Urban Research Institute Limited, Melbourne, <https://www.ahuri.edu.au/research/final-reports/208>.
- Dalton, T., Hurley, J., Gharaie, E., Wakefield, R., and Horne, R. (2013) *Australian suburban house building: industry organisation, practices and constraints*, AHURI Final Report No. 213, Australian Housing and Urban Research Institute Limited, Melbourne, <https://www.ahuri.edu.au/research/final-reports/213>.
- Davis, S. J., N. S. Lewis, M. Shaner, S. Aggarwal, D. Arent, I. L. Azevedo, S. M. Benson, T. Bradley, J. Brouwer, Y. M. Chiang, C. T.M.Clack, A. Cohen, S. Doig, J. Edmonds, P. Fennell, C. B. Field, B. Hannegan, B. M. Hodge, M. I. Hoffert, E. Ingersoll, P. Jaramillo, K. S. Lackner, K. J. Mach, M. Mastrandrea, J. Ogden, P. F. Peterson, D. L. Sanchez, D. Sperling, J. Stagner, J. E. Trancik, C. J. Yang, and K. Caldeira (2018), 'Net-zero emissions energy systems', *Science*, vol. 360 (6396), doi:10.1126/science.aas9793.
- DCCEEW (2022) *Safeguard mechanism reforms—August 2022 consultation paper*, Department of Climate Change, Energy, the Environment and Water, Australian Government, accessed 1 May 2023, <https://consult.dcceew.gov.au/safeguard-mechanism-reform-consultation-paper>.
- De Groote, M., and Lefever, M. (2016) *Driving Transformational Change in the Construction Value Chain: Reaching the Untapped Potential*, Buildings Performance Institute Europe, Brussels and Berlin, accessed 1 May 2023, <https://bpie.eu/wp-content/uploads/2016/01/DrivingTransformationalChangeCVC2016.pdf>.
- Dembski, F., Wössner, U., Letzgus, M., Ruddat, M. and Yamu, C. (2020) 'Urban digital twins for smart cities and citizens: the case study of Herrenberg, Germany', *Sustainability*, vol. 12, no. 6, doi:10.3390/su12062307.
- Department of Communities and Local Government (2017) *50 years of the English Housing Survey*, Department of Communities and Local Government, UK, accessed 1 May 2023, <https://www.gov.uk/government/publications/50-years-of-the-english-housing-survey>.
- DISER (2020) *Technology roadmap discussion paper*, Department of Industry, Science, Energy and Resources, Australian Government, accessed 1 May 2023, <https://consult.industry.gov.au/australias-technology-investment-roadmap-discussion-paper>.
- Dorée, A. and Holmen, E. (2010) 'Achieving the unlikely: innovating in the loosely coupled construction system', *Construction Management and Economics*, vol. 22, no. 8: 827–838, doi:10.1080/0144619042000190225.
- Dubois, A. and Gadde, L.E. (2010) 'The construction industry as a loosely coupled system: implications for productivity and innovation', *Construction Management and Economics*, vol. 20: 621–631. doi:10.1080/01446190210163543
- Dufourmont, J. and Brown, E.G. (2020) *Jobs and skills in the circular economy: state of play and future pathways*, Circle Economy, accessed 1 May 2023, <https://www.circle-economy.com/resources/jobs-skills-in-the-circular-economy-state-of-play-and-future-pathways>.
- EA (2021) *Our position on climate change*, Engineers Australia, accessed 1 May 2023, <https://www.engineersaustralia.org.au/resource-centre/resource/climate-change-position-statement>.
- Eberhardt, L.C.M., Birgisdóttir, H., Birkved, M. (2019) 'Life cycle assessment of a Danish office building designed for disassembly', *Building Research & Information*, vol. 47: 666–680. doi:10.1080/09613218.2018.1517458
- ECRA and CSI (2017) *Development of state of the art techniques in cement manufacturing: trying to look ahead*, Revision 2017, CSI/ECRA-Technology Papers 2017, European Cement Research Academy, Dusseldorf and Geneva.
- Ehnert, F., Egermann, M. and Betsch, A. (2021) 'The role of niche and regime intermediaries in building partnerships for urban transitions towards sustainability', *Journal of Environmental Policy & Planning*, vol. 24, no. 2: 137–159, <https://doi.org/10.1080/1523908x.2021.1981266>.
- EU (2018) *Impacts of circular economy policies on the labour market*, European Commission, Brussels, Belgium, accessed 1 May 2023, https://circulareconomy.europa.eu/platform/sites/default/files/ec_2018_-_impacts_of_circular_economy_policies_on_the_labour_market.pdf.
- European Commission (2016) *Buying green!: A handbook on green public procurement*, 3rd edn, accessed 1 May 2023, <https://ec.europa.eu/environment/gpp/pdf/Buying-Green-Handbook-3rd-Edition.pdf>.
- Fairgray, S., Tamásy, C. and Le Heron, R. (2012) 'New geographies of accumulation, globalising firm networks and the role of the Auckland region in the Australasian economy', *Urbani izziv*, vol. 23, s 2: s172–s185, doi:10.5379/urbani-izziv-en-2012-23-supplement-2-015.

- Favier, A., De Wolf, C., Scrivener, K. and Habert, G. (2018) *A sustainable future for the European cement and concrete industry technology: assessment for full decarbonisation of the industry by 2050*, Swiss Federal Institute of Technology (ETHZ), Zürich, Swiss Federal Institute of Technology (EPFL), Lausanne, and European Climate Foundation, [doi:10.3929/ethz-b-000301843](https://doi.org/10.3929/ethz-b-000301843).
- Fleming, G., Merrett, D. and Ville, S. (2004) *The Big End of Town: Big Business and Corporate Leadership in Twentieth-Century Australia*, Cambridge University Press, New York.
- Frew, W. (2021) 'NSW working on embodied carbon certificates for construction', *The Fifth Estate*, 24 June, 2021, accessed 1 May 2023, <https://thefifthestate.com.au/energy-lead/energy/nsw-could-soon-be-a-world-leader-in-construction-supply-chain-thank-you-david-chandler/>.
- Gardarsdottir, S., De Lena, E., Romano, M., Roussanaly, S., Voldsdun, M., Pérez-Calvo, David Berstad, J-F; Fu, C., Anantharaman, R., Sutter, D., Gazzani, M., Mazzotti, M. and Cinti, G. (2019) 'Comparison of technologies for CO₂ capture from cement production—Part 2: Cost analysis.' *Energies*, vol. 12, no. 3, [doi:10.3390/en12030542](https://doi.org/10.3390/en12030542).
- GBCA (2021) *Green Star Homes Standard: submission guidelines*, Green Building Council of Australia, accessed 1 May 2023, <https://new.gbca.org.au/green-star/green-star-strategy/future-homes/>.
- GBCA and thinkstep-anz (2021) *Embodied carbon and embodied energy in Australia's buildings*, Green Building Council of Australia and thinkstep-anz, Department of Industry, Science, Energy and Resources, Commonwealth of Australia, Sydney, accessed 1 May 2023, <https://www.thinkstep-anz.com/resrc/reports/embodied-carbon-and-embodied-energy-in-australias-buildings-gbca/>.
- GCCA (2019a) *GCCA sustainability charter*, Global Cement and Concrete Association, accessed 1 May 2023, <https://gcccassociation.org/sustainability-innovation/sustainability-charter-and-guidelines/>.
- GCCA (2019b) 'GCCA welcomes new member companies from Guatemala and Cyprus, new affiliates from Australia and Germany', *Global Cement and Concrete Association*, accessed 1 May 2023, <https://gcccassociation.org/news/gcca-welcomes-new-member-companies-from-guatemala-and-cyprus-new-affiliates-from-australia-and-germany/>.
- GCCA (2021) *Concrete future: The GCCA 2050 Cement and Concrete Industry roadmap for net zero concrete*, Global Cement and Concrete Association, accessed 1 May 2023, <https://gcccassociation.org/concretefuture/>.
- Gecz, J. 2019. 'IBISWorld', *Journal of Business & Finance Librarianship*, vol 24 no 1-2: 64-68. [doi:10.1080/08963568.2019.1660128](https://doi.org/10.1080/08963568.2019.1660128).
- Geissdoerfer, M., Savaget, P., Bocken, N. and Hultink, E. (2017) 'The circular economy: a new sustainability paradigm?', *Journal of Cleaner Production*, vol. 143: 757-768, [doi:10.1016/j.jclepro.2016.12.048](https://doi.org/10.1016/j.jclepro.2016.12.048).
- Gieseckam, J., Barrett, J. and Taylor, P. (2015) 'Construction sector views on low carbon building materials', *Building Research & Information*, vol. 44, no. 4: 423-444, [doi:10.1080/09613218.2016.1086872](https://doi.org/10.1080/09613218.2016.1086872).
- Gilbert, C., Rowley, S., Gurran, N., Leishman, C., Mouritz, M., Raynor, K. and Cornell, C. (2020) *Urban regulation and diverse housing supply: An Investigative Panel*, AHURI Final Report No. 349, Australian Housing and Urban Research Institute Limited, Melbourne, <https://www.ahuri.edu.au/research/final-reports/349>, doi:10.18408/ahuri7321501.
- GlobalABC/IEA/UNEP (2020) *GlobalABC roadmap for buildings and construction: towards a zero-emission, efficient and resilient buildings and construction sector*, Global Alliance for Buildings and Construction, International Energy Agency, and the United Nations Environment Programme, IEA, Paris, accessed 1 May 2023, <https://globalabc.org/roadmaps-buildings-and-construction>.
- Gosling, J., Towill, D.R., Naim, M.M. and Dainty, A. (2015) 'Principles for the design and operation of engineer-to-order supply chains in the construction sector', *Production Planning and Control*, vol. 26, no. 3: 203-218. [doi:10.1080/09537287.2014.880816](https://doi.org/10.1080/09537287.2014.880816).
- Gu, H., Liang, S. and Bergman, R. (2020) 'Comparison of building construction and life-cycle cost for a high-rise mass timber building with its concrete alternative', *Forest Products Journal*, vol. 70, no. 4: 482-492. [doi:10.13073/fpj-d-20-00052](https://doi.org/10.13073/fpj-d-20-00052).
- Gurran, N., Rowley, S., Milligan, V., Randolph, B., Phibbs, P., Gilbert, C., James, A., Troy, L. and Nouwelant, R. (2018) *Inquiry into increasing affordable housing supply: Evidence-based principles and strategies for Australian policy and practice*, AHURI Final Report No. 300, Australian Housing and Urban Research Institute Limited, Melbourne, <https://www.ahuri.edu.au/research/final-reports/300>, doi:10.18408/ahuri-7313001.
- Habert, G., Miller, S.A., John, V.M., Provis, J.L., Favier, A., Horvath, A. and Scrivener, K.L. (2020) 'Environmental impacts and decarbonization strategies in the cement and concrete industries', *Nature Reviews Earth & Environment*, vol. 1: 559-573, [doi:10.1038/s43017-020-0093-3](https://doi.org/10.1038/s43017-020-0093-3).

- Hafner, A. and Schäfer, S. (2017) 'Comparative LCA study of different timber and mineral buildings and calculation method for substitution factors on building level', *Journal of Cleaner Production*, vol. 167: 630–642, [doi:10.1016/j.jclepro.2017.08.203](https://doi.org/10.1016/j.jclepro.2017.08.203).
- Hasan, A., Elmualim, A., Rameezdeen, R., Baroudi, B. and Marshall, A. (2018) 'An exploratory study on the impact of mobile ICT on productivity in construction projects', *Built Environment Project and Asset Management*, vol. 8, no. 3: 320–332, [doi:10.1108/bepam-10-2017-0080](https://doi.org/10.1108/bepam-10-2017-0080).
- Hashimoto, S., Tanikawa, H. and Moriguchi, Y. (2007) 'Where will large amounts of materials accumulated within the economy go? A material flow analysis of construction minerals for Japan', *Waste Management*, vol. 27, no. 12: 1725–1738. [doi:10.1016/j.wasman.2006.10.009](https://doi.org/10.1016/j.wasman.2006.10.009).
- Honic, M., Kovacic, I. and Rechberger, H. (2019) 'Improving the recycling potential of buildings through material passports (MP): An Austrian case study', *Journal of Cleaner Production*, vol. 217: 787–797, [doi:10.1016/j.jclepro.2019.01.212](https://doi.org/10.1016/j.jclepro.2019.01.212).
- Horne, R. (2009) 'Life cycle assessment: origins, principles and context' in R. Horne, T. Grant and K. Verghese (eds), *Life Cycle Assessment: Principles, Practice and Prospects*, CSIRO Publishing, Melbourne.
- Houghton, J. (2021) *Timber usage in residential construction 2017–18 dataset: Report on methodology and results*, Forest & Wood Products Australia, accessed 1 May 2023, <https://fwpa.com.au/timber-usage-in-residential-construction-2017-18-dataset-report-on-methodology-and-results/>.
- Howe, R. (1988) *New houses for old: fifty years of public housing in Victoria, 1938–1988*, Ministry of Housing and Construction, Melbourne.
- Huang, T., Shi, F., Tanikawa, H., Fei, J., Han, J. (2013) 'Materials demand and environmental impact of buildings construction and demolition in China based on dynamic material flow analysis', *Resources, Conservation and Recycling*, vol. 72: 91–101, [doi:10.1016/j.resconrec.2012.12.013](https://doi.org/10.1016/j.resconrec.2012.12.013).
- Hurley, J., Taylor, E. and Dodson, J. (2017) 'Getting dense: why has urban consolidation been so difficult?', in J. Hurley, E. Taylor, J. Dodson, K. Vella and N. Sipe (eds), *The Routledge Handbook of Australian Urban and Regional Planning*, Routledge: 123–136.
- IAI (2021) *Aluminium sector greenhouse gas pathways to 2050*, International Aluminium Institute, accessed 1 May 2023, <https://international-aluminium.org/resource/aluminium-sector-greenhouse-gas-pathways-to-2050-2021/>.
- ICE (2022) *Low carbon concrete routemap: setting the agenda for a path to net zero*, Institute of Civil Engineers UK, accessed 1 May 2023, https://www.ice.org.uk/media/200i0yqd/2022-04-26-low-carbon-concrete-routemap-final_rev.pdf.
- IEA (2018) *Technology roadmap: low-carbon transition in the cement industry*, International Energy Agency, accessed 1 May 2023, <https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry>.
- IEA (2019) *Perspectives for the clean energy transition: the critical role of buildings*, International Energy Agency, accessed 1 May 2023, <https://www.iea.org/reports/the-critical-role-of-buildings>.
- IEA (2020) *Iron and steel technology roadmap: towards more sustainable steelmaking*, International Energy Agency, accessed 1 May 2023, <https://www.iea.org/reports/iron-and-steel-technology-roadmap>.
- IGCC (2019) *IGCC in 2022: Investing for a climate resilient net zero emissions economy*, Investor Group on Climate Change, accessed 1 May 2023, [https://igcc.org.au/wp-content/uploads/2020/07/IGCC-in-2022-investing-for-climate-resilient-netzero-emissions-economy.pdf](https://igcc.org.au/wp-content/uploads/2020/07/IGCC-in-2022-investing-for-climate-resilient-net-zero-emissions-economy.pdf).
- InfraBuild (2021) *Sustainability Report 2021*, accessed 1 May 2023, <https://www.infrabuild.com/sustainability/sustainability-reports/>.
- Ingemarsdotter, E., Jamsin, E., Kortuem, G. and Balkenende, R. (2019) 'Circular strategies enabled by the internet of things: a framework and analysis of current practice', *Sustainability*, vol. 11, no. 20. [doi:10.3390/su11205689](https://doi.org/10.3390/su11205689).
- IPCC (2018) *Global warming of 1.5°C: Intergovernmental Panel on Climate Change*, WMO and UNEP, accessed 1 May 2023, <http://www.ipcc.ch/report/sr15/>.
- IPCC (2022) *Climate change 2022: mitigation of climate change, contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, IPPC Intergovernmental Panel on Climate Change, Cambridge University Press, UK & USA, accessed 1 May 2023, <https://www.ipcc.ch/report/ar6/wg3/>.
- Isaksson, R., Johansson, P. and Fischer, K. (2010) 'Detecting supply chain innovation potential for sustainable development', *Journal of Business Ethics*, vol. 97, no. 3: 425–442. [doi:10.1007/s10551-010-0516-z](https://doi.org/10.1007/s10551-010-0516-z).

- Jayalath, A., Navaratnam, S., Ngo, T., Mendis, P., Hewson, N. and Aye, L. (2020) 'Life cycle performance of cross laminated timber mid-rise residential buildings in Australia', *Energy and Buildings*, vol. 223, [doi:10.1016/j.enbuild.2020.110091](https://doi.org/10.1016/j.enbuild.2020.110091).
- Jenkin, B. (2018) *Next generation plantation investment research project benchmarking analysis: Part 1 Australia's history of plantation development, policy and incentives*, The University of Melbourne, accessed 1 May 2023, <https://blogs.unimelb.edu.au/nextgenplantations/#tab187>.
- Jenkin, B., Keenan, R. and Bull, L. (2019) *Tree plantation investment and partnerships in Australia: an analysis of past experiences*, The University of Melbourne, School of Ecosystem and Forest Sciences, accessed 1 May 2023, <https://blogs.unimelb.edu.au/nextgenplantations/#tab187>.
- Kaza, S., Yao, L.C., Bhada-Tata, P. and van Woerden, F. (2018) *What a waste 2.0: a global snapshot of solid waste management to 2050*, World Bank, accessed 1 May 2023, <https://openknowledge.worldbank.org/handle/10986/30317>.
- Kelly, A. (2021a) *Cement and Lime Manufacturing in Australia C2031*, IBISWorld, IBISWorld.com.
- Kelly, A. (2021b) *Ready-Mixed Concrete Manufacturing in Australia C2033*, IBISWorld, IBISWorld.com.
- Kelly, A. (2022a) *House construction in Australia E3011*, IBISWorld, IBISWorld.com.
- Kelly, A. (2022b) *Multi-unit apartment and townhouse construction in Australia E3019*, IBISWorld, IBISWorld.com.
- Kelly, A. (2022c) *Structural steel fabricating in Australia*, IBISWorld, IBISWorld.com.
- Kelly, A. (2022d) *Fabricated wood manufacturing in Australia*, IBISWorld, IBISWorld.com.
- Kim, D. and Chanchlani, H.M. (2018) 'Influence of the built environment on the spatiotemporal variation of pedestrian collision in Seoul: an application of big data', *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2672, no. 35: 90–100, [doi:10.1177/0361198118793496](https://doi.org/10.1177/0361198118793496).
- Kivimaa, P., Boon, W., Hyysalo, S. and Klerkx, L. (2019) 'Towards a typology of intermediaries in sustainability transitions: a systematic review and a research agenda', *Research Policy*, vol. 48, no. 4: 1062–1075, [doi:10.1016/j.respol.2018.10.006](https://doi.org/10.1016/j.respol.2018.10.006).
- Larsen, J., Patterson, Z. and El-Geneidy, A. (2013) 'Build it. But where? The use of geographic information systems in identifying locations for new cycling infrastructure', *International Journal of Sustainable Transportation*, vol. 7, no. 4: 299–317, [doi:10.1080/15568318.2011.631098](https://doi.org/10.1080/15568318.2011.631098).
- Larson, S.M. (2012) *The rise of Professionalism: Monopolies of Competence and Sheltered Market*, Transaction Publisher, New Brunswick, USA.
- Laubinger, F., Lanzi, E. and Chateau, J. (2020) *Labour market consequences of a transition to a circular economy: a review paper*, OECD Environment Working Papers No. 162, OECD, accessed 1 May 2023, [https://one.oecd.org/document/ENV/WKP\(2020\)9/En/pdf](https://one.oecd.org/document/ENV/WKP(2020)9/En/pdf).
- Lavisci, P., Marfella, G. and Winson-Geideman, K. (2020) 'Mid-rise wood structures in Australia: the wood solutions initiatives and results', *World Conference on Timber Engineering*, Santiago, Chile.
- Lehne, J. and Preston, F. (2018) 'Making concrete change: innovation in low-carbon cement and concrete', *Chatham House Report*, The Royal Institute of International Affairs and Chatham House, London, accessed 1 May 2023, <https://www.chathamhouse.org/2018/06/making-concrete-change-innovation-low-carbon-cement-and-concrete>.
- Leviäkangas, P., Mok Paik, S. and Moon, S. (2017) 'Keeping up with the pace of digitization: the case of the Australian construction industry', *Technology in Society*, vol. 50: 33–43, [doi:10.1016/j.techsoc.2017.04.003](https://doi.org/10.1016/j.techsoc.2017.04.003).
- Li, S., Foliente, G., Seo, S., Rismanchi, B. and Aye, L. (2021) 'Multi-scale life cycle energy analysis of residential buildings in Victoria, Australia: a typology perspective', *Building and Environment*, vol. 195, art. 107723. [doi:10.1016/j.buildenv.2021.107723](https://doi.org/10.1016/j.buildenv.2021.107723).
- Llorente-González, L.J. and Vence, X. (2020) 'How labour-intensive is the circular economy? A policy-orientated structural analysis of the repair, reuse and recycling activities in the European Union', *Resources, Conservation and Recycling*, no. 162, [doi:10.1016/j.resconrec.2020.105033](https://doi.org/10.1016/j.resconrec.2020.105033).
- Lu, H.R., El Hanandeh, A., and Gilbert, B.P. (2017) 'A comparative life cycle study of alternative materials for Australian multi-storey apartment building frame constructions: environmental and economic perspective', *Journal of Cleaner Production*, no. 166: 458–473, [doi:10.1016/j.jclepro.2017.08.065](https://doi.org/10.1016/j.jclepro.2017.08.065).
- Maddox, T.M., Rumsfeld, R.S. and Payne, P.R.O. (2019) 'Questions for artificial intelligence in health care', *JAMA*, vol. 321, no. 1: 31–32, <https://www.ncbi.nlm.nih.gov/pubmed/30535130>, [doi:10.1001/jama.2018.18932](https://doi.org/10.1001/jama.2018.18932).

- Martin, D. (2022) *Metal roof and guttering manufacturing in Australia*, IBIS World, IBISWorld.com.
- Matthews, E., Amann, C., Bringezu, S., Fischer-Kowalski, M., Hüttler, W., Kleijn, R., Moriguchi, Y., Ottke, C., Rodenburg, E., Rogich, D. and Schandl, H. (2000) *The weight of nations: material outflows from industrial economies*, World Resources Institute, Washington.
- Matyjas, Z. (2014) 'The role of the structure-conduct-performance paradigm for the development of industrial organization economics and strategic management', *Journal of Positive Management*, vol. 5, no. 2, [doi:10.12775/jpm.2014.013](https://doi.org/10.12775/jpm.2014.013).
- Meacham, B.J. (2016) 'Sustainability and resiliency objectives in performance building regulations', *Building Research & Information*, vol. 44, no. 5–6: 474–489, [doi:10.1080/09613218.2016.1142330](https://doi.org/10.1080/09613218.2016.1142330).
- Meglin, R., Kytzia, S. and Habert, G. (2022) 'Regional circular economy of building materials: environmental and economic assessment combining material flow analysis, input–output analyses, and life cycle assessment', *Journal of Industrial Ecology*, vol. 26, no. 2: 562–576, [doi:10.1111/jiec.13205](https://doi.org/10.1111/jiec.13205).
- Milligan, V. and Tiernan, A. (2011) 'No home for housing: the situation of the Commonwealth's housing policy advisory function', *Australian Journal of Public Administration*, vol. 70, no. 4: 391–407. [doi:10.1111/j.1467-8500.2011.00746.x](https://doi.org/10.1111/j.1467-8500.2011.00746.x).
- Moore, T., Berry, S. and Ambrose, M. (2019) 'Aiming for mediocrity: the case of Australian housing thermal performance', *Energy Policy*, vol. 132: 602–610, [doi:10.1016/j.enpol.2019.06.017](https://doi.org/10.1016/j.enpol.2019.06.017).
- Mosca, M. (2016) 'Industrial organization', in G F. Kurz and M. Heinz (eds), *Handbook on the History of Economic Analysis Vol. III*, Edward Elgar Publishing: 291–304.
- Moss, T. (2009) 'Intermediaries and the governance of socio-technical networks in transition', *Environment and Planning A: Economy and Space*, vol. 41, no. 6: 1480–1495, [doi:10.1068/a4116](https://doi.org/10.1068/a4116).
- Muller, F., Saddler, H. and Melville-Rea, H. (2021) *Carbon border adjustments: what are they and how will they impact Australia?* The Australia Institute.
- Müller, J.M., Kiel, D. and Voigt, K.-I. (2018) 'What drives the implementation of industry 4.0? The role of opportunities and challenges in the context of sustainability', *Sustainability*, vol. 10, no. 1. [doi:10.3390/su10010247](https://doi.org/10.3390/su10010247).
- Munaro, M.R., Tavares, S.F., Bragança, L. (2020) 'Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment', *Journal of Cleaner Production*, vol. 260, 121134. [doi:10.1016/j.jclepro.2020.121134](https://doi.org/10.1016/j.jclepro.2020.121134).
- NABERS (2023) *Climate active carbon neutral building certification*, National Administrator, NSW Government, accessed 1 May 2023, <https://www.nabers.gov.au/>.
- Net-Zero Steel Initiative (2021) *Sector transition strategy*, Mission Possible Partnership, accessed 1 May 2023, www.missionpossiblepartnership.org.
- Newman, C., Edwards, D., Martek, I., Lai, J., Didibhuku Thwala, W. and Rillie, I. (2020) 'Industry 4.0 deployment in the construction industry: a bibliometric literature review and UK-based case study', *Smart and Sustainable Built Environment*, vol. 10, no. 4: 557–580, [doi:10.1108/sasbe-02-2020-0016](https://doi.org/10.1108/sasbe-02-2020-0016).
- NHFIC (2020) *State of the nation's housing report 2020*, National Housing Finance and Investment Corporation, accessed 1 May 2023, https://www.nhfic.gov.au/sites/default/files/2022-10/nhfic_state-of-the-nations-housing-report_accessible-updated.pdf.
- Norouzi, M., Chàfer, M., Cabeza, L.F., Jiménez, L., Boer, D. (2021) 'Circular economy in the building and construction sector: A scientific evolution analysis', *Journal of Building Engineering*, vol 44, 102704, [doi:10.1016/j.jobe.2021.102704](https://doi.org/10.1016/j.jobe.2021.102704).
- North, D.C. (1990) *Institutions, Institutional Change and Economic Performance*, Cambridge University Press, Cambridge.
- Nuñez-Cacho, P., Górecki, J., Molina-Moreno, V., Corpas-Iglesias, F. (2018) 'What Gets Measured, Gets Done: Development of a Circular Economy Measurement Scale for Building Industry', *Sustainability*, vol. 10, 2340. [doi:10.3390/su10072340](https://doi.org/10.3390/su10072340).
- OECD (2019) *Global material resources outlook to 2060* (2018 edn.), OECD Publishing, [doi:10.1787/9789264307452-en](https://doi.org/10.1787/9789264307452-en).
- OECD (2020) *Environment at a glance 2020*, OECD Publishing, [doi:10.1787/19964064](https://doi.org/10.1787/19964064).
- Olawumi, T.O. and Chan, D.W.M (2019) 'An empirical survey of the perceived benefits of executing BIM and sustainability practices in the built environment', *Construction Innovation*, vol. 19, no. 3: 321–342, [doi:10.1108/ci-08-2018-0065](https://doi.org/10.1108/ci-08-2018-0065).

- Ong, R., Dalton, T., Gurran, N., Phelps, C., Rowley, S. and Wood, G. (2017) *Housing supply responsiveness in Australia: distribution, drivers and institutional settings*, AHURI Final Report No. 281, Australian Housing and Urban Research Institute Limited, Melbourne, <https://www.ahuri.edu.au/research/final-reports/281>, doi:10.18408/ahuri-8107301.
- Ouellet-Plamondon, C.M. and Habert, G. (2016) 'Self-compacted clay based concrete (SCCC): proof-of-concept', *Journal of Cleaner Production*, vol. 117: 160–168, [doi:10.1016/j.jclepro.2015.12.048](https://doi.org/10.1016/j.jclepro.2015.12.048).
- Panteli, C., Kyllili, A., Stasiuliene, L., Seduikyte, L., Fokaides, P.A. (2018) 'A framework for building overhang design using Building Information Modeling and Life Cycle Assessment', *Journal of Building Engineering*, vol. 20, 248–255. [doi:10.1016/j.jobe.2018.07.022](https://doi.org/10.1016/j.jobe.2018.07.022).
- Park, J. and Tucker, R. (2016) 'Overcoming barriers to the reuse of construction waste material in Australia: a review of the literature', *International Journal of Construction Management*, vol. 17, no. 3: 228–237, [doi:10.1080/15623599.2016.1192248](https://doi.org/10.1080/15623599.2016.1192248).
- Parliament of Australia (2023) *Exposure draft explanatory materials: Housing Australia Future Fund Bill 2023*, National Housing Supply and Affordability Council Bill 2023, Treasury Laws Amendment (Housing Measures No. 1) Bill 2023, Australian Government.
- Passer, A., Lasvaux, S., Allacker, K., De Lathauwer, D., Spirinckx, C., Wittstock, B., Kellenberger, D., Gschösser, F., Wall, J. and Wallbaum, H. (2015) 'Environmental product declarations entering the building sector: critical reflections based on 5 to 10 years experience in different European countries', *The International Journal of Life Cycle Assessment*, vol. 20, no. 9: 1199–1212, [doi:10.1007/s11367-015-0926-3](https://doi.org/10.1007/s11367-015-0926-3).
- Paton-Cole, V.P. and Gad, E.F. (2017) 'Understanding the benefits of constructing a residential house with a heart of cold-formed steel', *AUBEA 2017: Australasian Universities Building Education Association Conference*.
- Perera, S., Jin, X., Samaratunga, M. and Gunasekara, K. (2021) *Digitalisation of construction: detailed report on digitalisation of design and construction of class 2 buildings in New South Wales*, Construct NSW and c4SMC, Western Sydney University.
- Perinotto, T. (2017) 'Nightingale reaches the village scale – now "anything is possible"', *The Fifth Estate*, accessed 20 April 2023, <http://thefifthestate.com.au/innovation/residential-2/nightingale-reaches-the-village-scale-now-anything-is-possible/>.
- Perinotto, T. (2022) 'The prefab timber and building supply business is booming', *The Fifth Estate*, accessed 1 May 2023, [https://thefifthestate.com.au/innovation/building-construction/the-prefab-timber-and-building-supply-business-is-booming/](http://thefifthestate.com.au/innovation/building-construction/the-prefab-timber-and-building-supply-business-is-booming/).
- Perry, M., Pechev, L., Lam, B. and Binney, J. (2021) *Estimating the benefits of an emissions reduction fund method for the use of timber products in buildings*, Forest & Wood Products Australia, <https://fwpa.com.au/estimating-the-benefits-of-an-emissions-reduction-fund-method-for-the-use-of-timber-products-in-buildings/>.
- Pickin, J., Wardle, C., O'Farrell, K., Nyunt, P. and Donovan, S. (2020) *National Waste Report 2020*, Department of Agriculture, Water and the Environment, accessed 1 May 2023, <https://www.dcceew.gov.au/environment/protection/waste/national-waste-reports/2020>.
- Potting, J., Hekkert, M.P., Worrell, E. and Hanemaaijer, A. (2017) 'Circular economy: measuring innovation in the product chain', *Planbureau Voor de Leefomgevin* [Netherlands Environmental Assessment Agency], no. 2544 (January), accessed 1 May 2023, <http://localhost/handle/1874/358310>.
- Prasad, D., Kuru, A., Oldfield, P., Ding, L., Malay, D., Noller, C. and He, B. (2021) *Race to net zero carbon: a climate emergency guide for new and existing buildings in Australia*, Low Carbon Institute, accessed 1 May 2023, <https://www.unsw.edu.au/content/dam/pdfs/unsw-adobe-websites/arts-design-architecture/built-environment/net-zero-guide/2023-01-24-Net-Zero-guide-v1b-online-version.pdf>.
- Responsible Steel (2021a) *Building a sustainable future for steel: all about responsible steel*, accessed 1 May 2023, <https://www.responsiblesteel.org/about/>.
- Responsible Steel (2021b) *Responsible steel standard*, accessed 1 May 2023, <https://www.responsiblesteel.org/>.
- Rezaei, J. (2019) 'Sustainable supplier selection: a process view', in J. Sarkis (ed.), *The Handbook on the Sustainable Supply Chain*, Edward Elgar, Northampton, MA.
- Riazi, S.R.M., Zainuddin, M.F., Nawi, M.N.M., Musa, S. and Lee, A. (2020) 'A critical review of fragmentation issues in the construction industry', *Talent Development & Excellence*, vol. 12, no. 2: 1510–1521, <http://iratde.com/index.php/jtde/article/view/545>.

- Robati, M. and Oldfield, P. (2022) 'The embodied carbon of mass timber and concrete buildings in Australia: an uncertainty analysis', *Building and Environment*, vol. 214, art. 108944, doi:10.1016/j.buildenv.2022.108944.
- Roberts, P. (2022) 'BlueScope moves to reline blast furnace', *Australian Manufacturing Forum*, accessed 26 June 2022, <https://www.aumanufacturing.com.au/bluescope-moves-to-reline-blast-furnace>.
- Rowley, S., and Phibbs, P. (2012) *Delivering diverse and affordable housing on infill development sites*, AHURI Final Report No. 193, Australian Housing and Urban Research Institute Limited, Melbourne, <https://www.ahuri.edu.au/research/final-reports/193>.
- Rowley, S., Gilbert, C., Gurran, N., Leishman, C. and Phelps, C. (2020) *The uneven distribution of housing supply, 2006–2016*, AHURI Final Report No. 334, Australian Housing and Urban Research Institute Limited, Melbourne, <https://www.ahuri.edu.au/research/final-reports/334>, doi:10.18408/ahuri-8118701.
- Sakin, M. & Kiroglu, Y. (2017) '3D printing of buildings: construction of the sustainable houses of the future by BIM', 9th International Conference on Sustainability in Energy and Buildings, SEB-17, 5–7 July 2017, Chania, Crete, Greece.
- Sarkis, J. (2019) 'The handbook on the sustainable supply chain: an introduction', in J. Sarkis (ed.) *Handbook on the Sustainable Supply Chain*, Edward Elgar, Northampton, MA: 1–10.
- Schmalensee, R. (1987) 'Industrial organization', in M. Milgate, P. Newman and J. Eatwell (eds), *The New Palgrave: A Dictionary of Economics*, Macmillan, London.
- Shergold, P. and Weir, B. (2018) *Building confidence: Improving the effectiveness of compliance and enforcement systems for the building and construction industry across Australia*. Building Ministers Forum, accessed 1 May 2023, <https://www.industry.gov.au/publications/building-confidence-building-ministers-forum-expert-assessment>.
- Shi, X., Zhang, X., Dong, C. and Wen, S. (2018) 'Economic performance and emission reduction of supply chains in different power structures: perspective of sustainable investment', *Energies*, vol. 11, no. 4, doi:10.3390/en11040983.
- Shojaei, A., Ketabi, R., Razkenari, M., Hakim, H. and Wang, J. (2021) 'Enabling a circular economy in the built environment sector through blockchain technology', *Journal of Cleaner Production*, vol. 294, doi:10.1016/j.jclepro.2021.126352.
- Shooshtarian, S., Maqsood, T., Wong, P., Khalfan, M. and Yang, R.J. (2019) *Resource circular economy: Opportunities to reduce waste disposal across the supply chain – Timber*, Sustainable Built Environment National Research Centre (SBEnrc), accessed 1 May 2023, <https://sbencrc.com.au/research-programs/1-65/>.
- Shooshtarian, S., Maqsood, T., Wong, P., Khalfan, M. and Yang, R.J. (2020) 'Market development for construction and demolition waste stream in Australia', *Journal of Construction Engineering, Management & Innovation*, vol. 3, no. 3: 220–231, doi:10.31462/jcemi.2020.03220231.
- Standing Committee on Agriculture and Water Resources (2021) *Aussie logs for Aussie jobs: Inquiry into timber supply chain constraints in the Australian plantation sector*, Parliament of the Commonwealth of Australia, House of Representatives, accessed 1 May 2023, https://parlinfo.aph.gov.au/parlInfo/download/committees/reportrep/024630/toc_pdf/AussielogsforAussiejobs.pdf;fileType=application%2Fpdf.
- Stephan, A. and Athanassiadis, A. (2017) 'Quantifying and mapping embodied environmental requirements of urban building stocks', *Building and Environment*, vol. 114: 187–202, doi:10.1016/j.buildenv.2016.11.043.
- The Treasury (ND) 'The National Housing Supply Council', Australian Government, accessed 1 May 2023, <https://treasury.gov.au/programs-initiatives-consumers-community/the-national-housing-supply-council>.
- Thomas, D. and Ding, G. (2018) 'Comparing the performance of brick and timber in residential buildings: the case of Australia', *Energy and Buildings*, vol. 159: 136–147, doi:10.1016/j.enbuild.2017.10.094.
- Troy, P.N. (2012) *Accommodating Australians: Commonwealth Government Involvement in Housing*, Federation Press, Annandale, NSW.
- TWG (2021) *The net-zero steel pathway methodology project*, The Net-Zero Steel Pathway Methodology Project Steering Group, accessed 1 May 2023, <https://www.netzerosteelpathwayproject.com/>.
- United Nations (2022) *Summary of Global Climate Action at COP 27*, United Nations Marrakech Partnership, accessed 1 May 2023, https://unfccc.int/sites/default/files/resource/GCA_COP27_Summary_of_Global_Climate_Action_at_COP_27_1711.pdf.
- van der Heijden, J. (2017) *Innovations in Urban Climate Governance: Voluntary Programs for Low-Carbon Buildings and Cities*, Cambridge University Press, Cambridge.

- VDZ (2021) *Decarbonisation pathways for the Australian cement and concrete sector*, The Cement Industry Federation, Cement Concrete and Aggregates Australia, SmartCrete CRC and RACE for 2030 CRC, accessed 1 May 2023, https://cement.org.au/wp-content/uploads/2021/11/Full_Report_Decarbonisation_Pathways_web_single_page.pdf
- Venkataraman, M., Csereklyei, Z., Aisbett, E., Rahbari, A., Jotzo, F., Lord, M. and Pye, J. (2022) 'Zero-carbon steel production: the opportunities and role for Australia', *Energy Policy*, vol. 163, art. 112811. [doi:10.1016/j.enpol.2022.112811](https://doi.org/10.1016/j.enpol.2022.112811).
- Voldsgaard, M., Gardarsdottir S., De Lena, E., Pérez-Calvo, J.-F., Jamali, A., Berstad, D., Fu, C., Romano, M., Roussanaly, S., Anantharaman, R., Hoppe, H., Sutter, D., Mazzotti, M., Gazzani, M., Cinti, G. and Jordal, K. (2019) 'Comparison of technologies for CO₂ capture from cement production—Part 1: technical evaluation', *Energies*, vol. 12, no. 3. [doi:10.3390/en12030559](https://doi.org/10.3390/en12030559).
- Watson, K. (2005) *Guide to the Australian steel framing industry for new fabricators*. National Association of Steel-Framed Housing, NASH, accessed 1 May 2023, https://www.nash.asn.au/wp-content/uploads/2022/04/NASH_New_Ent_Guide_Aus_StFr_Ind.pdf.
- WBCSD (2003) *The cement sustainability initiative: agenda for action*, World Business Council for Sustainable Development, accessed 1 May 2023, <https://www.wbcsd.org/Sector-Projects/Cement-Sustainability-Initiative/Resources/CSI-Our-Agenda-for-Action>.
- Wendehorst, R. (2011) *Baustoffkunde*, 27th edition, fully revised by Günter Neroth, Wiesbaden: Vieweg + Teubner (Praxis).
- Whittle, L., Lock, P. and Hug, B. (2019) *Economic potential for new plantation establishment in Australia*, Australian Bureau of Agricultural and Resource Economics and Sciences, Department of Agriculture and Water Resources, accessed 1 May 2023, https://www.agriculture.gov.au/sites/default/files/abares/documents/PlantationEstablishmentOutlook2050_v1.0.0.pdf.
- Wood Solutions (2023) 'Mid-rise advisory resources', accessed 22 February 2023, <https://www.woodsolutions.com.au/mid-rise>.
- Woods, T. and Houghton, J. (2022) *Future market dynamics and potential impacts on Australian timber imports*, Forest and Wood Products Australia, accessed 1 May 2023, <https://fwpa.com.au/future-market-dynamics-and-potential-impacts-on-australian-timber-imports-interim-report-released/>.
- WSA (2021) 'Climate change and the production of iron and steel', World Steel Association, accessed 1 May 2023, <https://worldsteel.org/media-centre/press-releases/2021/climate-change-and-the-production-of-iron-and-steel/>.
- WSA (2022) 'World steel in figures', World Steel Association, accessed 1 May 2023, <https://worldsteel.org/steel-topics/statistics/world-steel-in-figures-2022/>.
- Xing, K., Pyung Kim, K. and Ness, D. (2020) 'Cloud-BIM enabled cyber-physical data and service platforms for building component reuse', *Sustainability*, vol. 12, no. 24, [doi:10.3390/su122410329](https://doi.org/10.3390/su122410329).
- Yu, M., Wiedmann, T., Crawford, R. and Tait, C. (2017) 'The carbon footprint of Australia's construction sector', *Procedia Engineering*, vol. 180: 211–220, [doi:10.1016/j.proeng.2017.04.180](https://doi.org/10.1016/j.proeng.2017.04.180).
- Zhang, C., Hu, M., Sprecher, B., Yang, X., Zhong, X., Li, C. and Tukker, A. (2021) 'Recycling potential in building energy renovation: A prospective study of the Dutch residential building stock up to 2050', *Journal of Cleaner Production*, vol. 301, art. 126835, [doi:10.1016/j.jclepro.2021.126835](https://doi.org/10.1016/j.jclepro.2021.126835).
- Zhang, Y., Lei, Z., Han, S., Bouferguene, A., Al-Hussein, M. (2020) 'Process-oriented framework to improve modular and offsite construction manufacturing performance', *Journal of Construction Engineering and Management*, vol. 146, art. 04020116, [doi:10.1061/\(ASCE\)CO.1943-7862.0001909](https://doi.org/10.1061/(ASCE)CO.1943-7862.0001909).

Appendix 1: Workshop material

Building materials in a circular economy: Workshop briefing paper for Section 4

Building materials in a circular economy

Workshop briefing paper

RMIT UNIVERSITY Centre for Urban Research

1. Introduction

This briefing paper informs the workshop for the research project Building Materials in a Circular Economy (2021-2022) on housing industry building materials supply chains. The project is funded by the Australian Housing and Urban Research Institute (AHURI). Led by RMIT, it is one of four linked projects underpinning the Inquiry into Housing in a Circular Economy led by Prof Ralph Horne and involving five Australian universities.

The workshop focus will be on the prospects for shifting to a circular economy in housing building materials. We know that a range of capabilities, models, practices, policies and incentives are required as we transition to a building materials circular economy by 2050. Multiple aspects of reuse and waste in material supply chains need to be considered. Two questions will guide the workshop:

1. Who are the key influencers in housing construction supply chains and how do they shape the choice and use of materials?
2. What supply-side drivers and dynamics could accelerate the contribution of building materials to decarbonising the housing system?

The workshop will be an online, invite-only event of selected experts and will not exceed 2 hours. It will consist of three parts. First, an open discussion of key priorities responding to the above two questions; second, a presentation of the industry analysis already undertaken by the research team, and, third, a facilitated conversation that critically assesses and reflects on the supply/demand side drivers that could increase CE and reduce embodied carbon in the production, distribution, and use of materials. An online virtual board will be used to help visualise input in the discussion.

The workshop will be recorded, and the recording will be used for the research in accordance with RMIT Research Ethics provisions. All contributions will be subsequently anonymised, and participants will be expected to observe the Chatham House Rule. This rule states:

When a meeting, or part thereof, is held under the Chatham House Rule, participants are free to use the information received, but neither the identity nor the affiliation of the speaker(s), nor that of any other participant, may be revealed.

The workshop will be chaired and facilitated by Prof Ralph Horne.

2. The circular economy: decarbonising the housing system

There are various definitions of the CE concept; this research adopts the following one:

We define the Circular Economy as a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling (Geissdoerfer et al 2017)

In 2013, 90.3 Mt CO₂e of emissions embodied in new materials flowed into the construction sector. This formed 18.1% of Australia's total emissions in that year. Residential building was

responsible for 21.5 Mt CO₂e emissions, or 24 % of the total (Yu et al. 2017, 217) of which:

cement, concrete, plasterboard, limestone, brick and other ceramics accounted for the largest embodied emissions (39.2%), other minerals accounted for 24.2%, iron & steel and timber contributed similar amount at around 9.8% and 9.3% respectively, other metals 9.2% and plastic, polymer and rubber 6.0%

Construction and demolition waste totalled 27 Mt, some 44% of the total waste managed by the waste and resource recovery sector (Pickin et al. 2020, xi).



The challenge that Australia faces in decarbonising the construction sector is shared globally. The Global Alliance for Buildings and Construction (GABC), a program supported by the International Energy Agency (IEA) and the United Nations (UN) Environment Program describes the challenge:

The buildings and construction sector is a highly “local” and “fragmented” industry, with no single group of large businesses having significant control of the stock and value chain. Innovation is slow, largely due to this fragmentation, and there is a lack of a common and international vision from the disparate actors in the sector. (GABC 2020, 13)

The challenge for the housing sector is to develop strategies for ‘long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling’ to reduce the consumption of carbon intensive materials going into the housing stock. Embodied carbon emissions flow from the manufacture, transport, construction and end of life disposal of building materials. The World Green Building Council (WGBC) demonstrates the urgency, noting the current pattern of growth

will consume vast amounts of natural resources, contributing to an expected doubling of the total global consumption of raw materials by around the middle of the century, significantly increasing the sector’s emissions and climate impact (WGBC 2019, 7)

In some European and Scandinavian countries and the USA, requirements are now in place to measure and report on embodied carbon in new buildings and infrastructure. The NSW government has also announced its intention to use the planning system to require the carbon intensity of new major developments to be reported.

3. The housing industry as an institution

An institutional approach is important to inform new ways to reduce embodied carbon in the housing system. It shows how industry fragmentation continues to shape the flow of building materials in housing construction. It focusses on industry actors and their patterned relationships that constitute supply chains and enable and constrain exchange processes. It also focuses on industry bodies that service and represent the industry. The institutional nature of housing production in Australia can be described by referring to three key features:

- Housing industry structure and operations
- Housing industry intermediaries representing the industry
- Housing industry supply chain industries

3.1 Housing industry structure and operations

Table 1 divides the housing industry into two main elements: detached housing and multi-unit apartments. It presents summary information on industry structure; industry composition; purchasers; fluctuating industry activity; globalisation – exports and imports; and industry regulation. Three features stand out with regard to the structure of the industry and the nature of the businesses that comprise them:

1. There is a limited presence of large companies by output in both house building and multi-unit and townhouse construction;
2. There is a heavy reliance on highly mobile sub-contractor labour forces with skill sets required to work with specific materials;
3. The dominant business model of builders involves them setting and securing a limited margin on cash flows for material purchases and work completed by sub-contractors.

A consequence of these features is that there are few companies with the necessary resources for internal R&D, innovation and strategy development which could be used for development of circular economy building construction methodologies and material use.

In addition, the regulation of energy efficiency and circular economy practices has been fraught and largely piecemeal when compared to more systemic approaches in other sectors. From the 1970s, state and territory governments promoted voluntary initiatives on energy efficiency, and it was not until 2003 that energy efficiency standards were mandated (2005 for multi-residential developments). Subsequently, requirements have been increased and in 2010 the 6-star standard was adopted.

Although limited, the research shows that the energy efficiency standards required by the Australian Building Codes Board (ABCB) have provided energy savings for new homes (Berry and Marker 2015). Underpinning this has been the Nationwide House Energy Rating Scheme (NatHERS) software tool used to assess plans and building specifications resulting in better insulation, double glazed windows, shading, sun smart dwelling orientation and solar panels.

Currently governments are considering whether to increase the star rating from 6 to 7.5 which would bring Australian standards closer to standard practice in the USA and Europe. There is no current regulation regarding circular economy, extended producer responsibility, or embodied energy/carbon relation to the sector in Australia.

In this context Australia has much to do in the development and implementation of energy efficiency regulation and circular economy building materials compared to most other Organisation for Economic Co-operation and Development (OECD) countries. Minimum standards and enabling measures lag comparable countries, which has resulted in Australia being well behind international best practice (Moore et al 2019).

3.2 Housing industry intermediaries

Intermediaries include membership organisations or agencies that provide advocacy and services for their members. They can drive change or resist change by seeking to maintain status quo arrangements. In the housing industry there are three main forms of intermediaries and Table 2 lists key intermediary organisations for each of these types.

3.3 Housing industry supply chains

Builders in the housing industry draw materials for house and multi-unit apartment construction from many supply chains. Housing industry builders draw products and services from at least seventeen industries listed in Table 3. All will need to change if there is to be a systematic and deep reduction, reuse, recycling and recovery of resources.

In the workshop we will present some of our analysis on these supply chains.



Table 1. The housing construction industry

Industry	House construction	Multi-unit apartment and townhouse construction
What is produced	Housing construction for households purchasing a house on land they own (58%); alterations, additions, renovations and improvements (22%); housing repairs and maintenance (13%); other services (6%).	Project management and construction generally for developers who own the land: multistorey apartment complexes (50%); townhouses and semi-detached terrace houses (30%); suburban and rural flats or units (5%); alterations and additions to existing buildings (15%). Apartments and townhouses are typically strata-titled.
Industry structure	<p><i>Low capital intensity</i> – contractors provide project management and trade skills and typically lease capital equipment, such as scaffolding, lifting and earthmoving equipment. Contractors in this labour-intensive industry rely on subcontractors who provide their own tools.</p> <p><i>Low concentration</i> – house construction broadly divides into two categories (a) many small-scale businesses with approximately half generating less than \$200,000 pa and 58% of businesses with no paid employees (b) 30 medium- to-large-scale firms (volume builders) each constructing more than 400 dwellings pa. using sub-contract labour with annual revenue exceeding \$50 million.</p> <p><i>Low/moderate innovation</i> – development of materials and tools has reduced skilled labour requirements and project managers are increasing their use of digital tools</p>	<p><i>Low capital intensity</i> – the main industry contribution to value comes from skilled labour and construction management services which do not require significant capital. Project capital is typically the responsibility of the developer.</p> <p><i>Low concentration</i> – The industry's four largest firms were expected to account for less than 20% of industry revenue in 2020-21 although the share has increased</p> <p><i>Barriers to entry</i> – builder registration, license to practice, member of industry associations with access to a pool of sub-contractors and arrangements with material suppliers</p> <p><i>Low/moderate innovation</i> – increasing use of digital technology in project management and innovative building materials</p>
Industry composition	The small business builders produce small numbers of houses each year. The larger companies known as the 'volume builders', such as Metricon, G.J. Gardner Homes, ABN Corporate Services, BGC Housing Group, MJH Group, Simonds Group, Burbank, Henley Homes, Hotondo Building, have market shares ranging between 1 and 3% of new house construction. These companies have been extending the geographic spread of their operations. Both the small builders and the volume builders rely on extensive sub-contracting and little direct employment.	Small-scale businesses dominate the industry. Over 3/4 of industry enterprises are small businesses with no paid employees. Approximately 56% of businesses generate less than \$200,000 in annual revenue. The industry includes some large-scale multi-unit builders such as Multiplex, Dylam, Pro-build, Hickory Group, Lendlease, Meriton, Geoccon, L U Simon, Parkview Construction, J Hutchinson. They have market shares ranging between 2 and 5% of annual apartment production totalling 28%. All builders rely on extensive sub-contracting and little direct employment.
Purchasers	Purchasers are overwhelmingly owner occupier households purchasing houses from the builder in new outer-suburban growth areas. Purchasers can also be rental investors	Developers recruit purchasers through 'pre-sales' contracting, which indicates demand, and a basis for obtaining development finance and contracting a builder. Purchasers are both owner occupier households and landlord investors
Fluctuating industry activity	Industry fluctuations are shaped by: interest rates; population growth and household formation; pricing of land and dwellings; income growth and distribution; and change in first home-owner assistance programs. House builders respond quickly to changes in demand. However, developer responses to changes in demand for apartments and town houses is lagged due to longer planning, financing and construction time frames.	
Globalisation – exports and imports	House and apartment builders are minimally involved in exports with the exception of Lendlease which operates in Australia, Asia, Europe, the Middle East and the Americas. Builders use some imported building materials and fixtures.	
Regulation	Regulations include local and state government building standards; builder registration; insurance; warranties; building permit approvals; planning regulation; noise and effluent pollution controls; disruption to existing businesses or residents; and occupational health and safety.	

Sources: IBISWorld reports and Dalton et al (2011), Dalton et al (2013), Ong et al (2017)

Table 2. Housing industry intermediaries

Industry associations	Professional associations	Civil society
Housing construction <ul style="list-style-type: none"> • Housing Industry Association • Master Builders Association 	<ul style="list-style-type: none"> • Australian Institute of Architects • Planning Institute of Australia • Engineers Australia • Australian Institute of Project Management • Australian Institute of Building Surveyors • Australian Institute of Quantity Surveyors • Australian Institute of Building • Building Services Contractors Association of Australia • Building Designers Association of Australia • Facility Management Association of Australia 	<ul style="list-style-type: none"> • Green Building Council of Australia • Australian Sustainable Built Environment Council • Alternative Technology Association • Beyond Zero Emissions • Renew • Energy Efficiency Council • Infrastructure Sustainability Council of Australia • Materials & Embodied Carbon Leaders' Alliance (MECLA)
Land development <ul style="list-style-type: none"> • Urban Development • Institute of Australia 		
Construction <ul style="list-style-type: none"> • Australian Construction Industry Forum • Australian Constructors Association • Civil Contractors Federation • Construction & Mining Equipment Industry Group 		
Property <ul style="list-style-type: none"> • Property Council of Australia • Real Estate Institute of Australia 		

Table 3. Tier 1 industries supplying materials and services to residential builders

<ul style="list-style-type: none"> • Wooden Structural Component Manufacturing • Fabricated wood manufacturing • Carpentry and joinery timber manufacturing • Carpentry Services • Plastering and Ceiling Services • Ready-mixed Concrete Services • Painting and Decorating Services • Clay Brick Manufacturing • Landscaping services • Tiling and Carpeting Services • Advertising Agencies • Surveying and Mapping Services • Architectural Services • Engineering Consulting • Construction Machinery and Operator Hire • Machinery and Scaffolding Rental • Solid Waste Collection Services
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4. The building materials industry: towards a circular economy

Multiple interventions drawn from a spectrum of possibilities will be required. We start considering these possibilities by using the four policy instrument categories, proposed by Ürge-Vorsatz et al. (2007), in Table 4 which presents summary accounts of recent initiatives aimed at increasing built environment energy efficiency and reductions in embodied carbon.

Table 4. Contemporary built environment energy efficiency and carbon reduction initiatives

Control and regulatory measures
<i>Control and regulatory measures refer to rules that apply to activities, processes or outcomes and are typically the responsibility of government.</i>
Contemporary examples are:
<ul style="list-style-type: none"> • NCC regulation commencing in 2010 requiring all new dwellings to be designed to meet a six-star energy efficiency level • The Australian Prudential Regulation Authority (APRA) is 'seeking to ensure that APRA-regulated institutions are managing the risks and opportunities that may arise from a changing climate'. • The NSW Government (2020) has committed to drive the uptake of sustainable building materials.
Economic and market-based instruments
<i>Economic and market-based instruments aim to modify the relations of existing markets and establish new markets by creating and reshaping market forces and price changes so as to modify the behaviour of public and private polluters so that they reduce GHG emissions.</i>
Contemporary examples are:
<ul style="list-style-type: none"> • The Clean Energy Regulator has created a voluntary market for carbon trading. • Both NSW and Victoria have established markets for tradeable certificates.
Fiscal instruments and incentives
<i>Fiscal instruments and incentives seek to modify market exchanges by supplementing the capacity of some categories of actors which gives them enhanced market power.</i>
Contemporary examples are:
<ul style="list-style-type: none"> • The Clean Energy Finance Corporation (CEFC) co-invests in new assets with companies which lowers the investment risk in innovative clean energy technologies and assets. • Government domestic solar energy household grant programs have supported the formation and growth of a domestic solar energy industry.
Support, information and voluntary action
<i>Support, information and voluntary action programs developed and run by government agencies, NGOs and companies aim to change the behaviours of target groups.</i>
Contemporary examples are:
<ul style="list-style-type: none"> • The GBCA Green Star Home program certifies designs and built outcomes that meet set criteria. • States and territories provide households with information about the energy efficiency of dwellings such as mandatory energy efficiency rating (ACT), and the Victorian Residential Efficiency Scorecard Initiative now being rolled out nationally. • Environmental Product Disclosures (EPDs) are standardised and verified documents presenting the results of product life cycle analyses. • Programs, such as the US based Al Gore led Climate Reality Project, Women's Environmental Leadership Australia (WELA), Climate Action Network Australia (CANA) and the Climate Leaders Coalition (CLC), are training and supporting business and community leaders to be educators and take action to develop climate solutions.

5. Workshop tasks and questions

A workshop agenda will be circulated prior to the workshop. This agenda will include:

- Introductions: participants background & engagement with housing materials supply chains;
- Insights from Project data analysis, and;
- Discussion and prioritisation of future initiatives.

The main focus will be on who the key influencers are in housing material supply chains and what measures could accelerate the transition to circular economy housing materials and practices.

Key questions that the workshop will discuss include the following:

1. What challenges are you aware of with current regulatory requirements?
2. How can we learn from our experiences with energy efficiency regulations for buildings, as we set minimum standards for circular economy building materials?
3. What inspection and verification regimes are required that will support independent verification of circular economy performance in future building materials supply chains?
4. What market incentives are required to encourage circular economy building materials?
5. What institutional models/organisations and structures are required to support knowledge, leadership, responsibility and stewardship in circular economy housing construction?

For example, under question 1 above, current standard building contracts specify the use of new materials which prevents the reuse of building materials even where this would be legitimate and would enhance circular economy outcomes. A facilitated discussion of each question will provide opportunities for participants to contribute expertise, experience and insights.

Sources

- APRA (2021). Prudential practice guide: Draft CPG 229 Climate Change Financial Risks, Australian Prudential Regulation Authority.
- Berry, S. and T. Marker (2015). Residential energy efficiency standards in Australia: where to next? *Energy Efficiency* 8: 963–974.
- Dalton, T., J. Hurley, E. Gharai, R. Wakefield and R. Horne (2013). Australian suburban house building: industry organisation, practices and constraints. AHURI Final Report No.213. Melbourne, Australian Housing and Urban Research Institute.
- Dalton, T., R. Wakefield and R. Horne (2011). Australian suburban house building: industry organisation, practices and constraints. AHURI Positioning Paper No.143. Melbourne, Australian Housing and Urban Research Institute.
- Department of Planning, Industry and Environment (2020) Net Zero Plan Stage 1:2020 – 2030, NSW Government
- Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular Economy – A new sustainability paradigm? *Journal of Cleaner Production*, 143, 757–768. <https://doi.org/10.1016/j.jclepro.2016.12.048>
- Global Alliance for Building and Construction (2020) GlobalABC Roadmap for Buildings and Construction 2020–2050: Towards a zero-emission, efficient, and resilient buildings and construction sector, IEA, Paris
- Moore, T., S. Berry and M. Ambrose (2019). Aiming for mediocrity: The case of Australian housing thermal performance. *Energy Policy* 132: 602–610.
- Ong, R., T. Dalton, N. Gurran, C. Phelps, S. Rowley and G. Wood (2017). Housing supply responsiveness in Australia: distribution, drivers and institutional settings. AHURI Final Report No. 281, Australian Housing and Urban Research Institute Limited, Melbourne
- Pickin, J., C. Wardle, K. O'Farrell, P. Nyunt and S. Donovan (2020). National Waste Report 2020, Department of Agriculture, Water and the Environment.
- Ürge-Vorsatz, D., Koeppel, S., & Mirasgedis, S. (2007). Appraisal of policy instruments for reducing buildings' CO₂ emissions. *Building Research & Information*, 35(4), 458–477. <https://doi.org/10.1080/09613210701327384>
- WGBC (2019) Bringing embodied carbon upfront: Coordinated action for the building and construction sector to tackle embodied carbon, World Green Building Council.
- Yu, M., T. Wiedmann, R. Crawford and C. Tait (2017). "The Carbon Footprint of Australia's Construction Sector." *Procedia Engineering* 180: 211–220.

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Workshop agenda for Section 4

Meeting	Workshop 'Building materials and a future Circular Economy'
Date	6th of May 2022
Time	12.00 pm – 2 pm
Location	Online (Microsoft Teams link)

1. Introductions

- 1.1 Participants background & engagement with building materials and/or circular economy
- 1.2 Presentation of research project in context of AHURI Industry Inquiry Program

2. Discussion of key priorities

- 2.1 Who are the key influencers in housing supply chains and how do they shape the choice and use of materials?
- 2.2 What supply-side drivers and dynamics could accelerate the contribution of building materials to decarbonising the housing system?

3. Research insights from project data analysis

4. Discussion and prioritisation of future initiatives towards circular economy housing materials and practices

- 4.1 What challenges are you aware of with current regulatory requirements?
- 4.2 How can we learn from our experiences with energy efficiency regulations for buildings, as we set minimum standards for circular economy building materials?
- 4.3 What inspection and verification regimes are required that will support independent verification of circular economy performance in future building materials supply chains?
- 4.4 What market incentives are required to encourage circular economy building materials?
- 4.5 What institutional models/organisations and structures are required to support knowledge, leadership, responsibility and stewardship in circular economy housing construction?

5. Concluding remarks

Appendix 2: Interview questions

Apartment documentation and site audit: Generic interview questions for Section 3

1. **Position in the organisation/project:** Can you please tell us what position you hold in your company and a little about your career and how you came to be working in the residential/building construction industry and this project in particular?
2. **Current project:** Can you please provide us with an overview of this residential construction project and your role in its design, financing, procurement and construction management? We are particularly interested to learn more about:
 - a. The conceiving and development of the proposal for this project and the main stages that precede its current construction.
 - b. The companies/actor groups that have been involved in the project's design, financing, procurement and construction management.
 - c. The way the market for this housing project was analysed and understood and informed the decision to proceed to construction.
 - d. The planning and regulatory requirements that have been used to assess the project proposal.
3. **Sustainability and circular economy framing:** Can you please provide us with an overview of the sustainability (including circular economy) objectives that were set for this project and the way in which they have been embedded in the project's design, procurement and construction management processes? We are particularly interested to learn more about:
 - a. Project sustainability objectives including the main impetus and timing of objective setting in project conception, development and operations.
 - b. The embedding of project sustainability objectives within the design, financing, procurement and construction management processes.
 - c. Regulatory requirements and project sustainability objectives within the design, financing, procurement and construction management processes.
 - d. Collaboration between professionals on sustainability in the project's design, financing, procurement and construction management processes.
 - e. Change in project sustainability objectives during the course of project conception, development and execution.
 - f. Sustainability innovation in the project, such as materials selection, supply chains, procurement, indoor air quality, etc.
 - g. Focus on attaining the requirements for a GreenStar rating or other accreditation schemes.

- h. Extension of sustainability thinking to explicit adoption of circular economy thinking in project design and execution.
 - i. Opportunities for extension of sustainability and/or circular economy measures in project design and execution.
 - j. Difficulties in implementing sustainability and/or circular economy measures in project design and execution.
4. **Learning from experience about sustainability and CE:** Can you please tell us about your approach to learning from past project experience in setting ambitious objectives and stretch targets and the way change can be introduced into project design, procurement and construction management processes? We are particularly interested to learn more about:
- a. Revisiting projects, examining key features and identifying and documenting learnings for future projects.
 - b. Engaging with future occupants during the design process, occupants and/or building managers after completion and occupation.
 - c. Considering and assessing what should happen at the building's 'end of life' and frameworks like GreenStar for this assessment.
 - d. Role of technologies, like BIM and Track and Trace in circular economy innovation in design, financing, procurement and construction management.

Institutions, actors and levers for change: Generic interview questions for Section 4

1. **Position in the organisation:** Can you please tell us what position you hold in this company and a little about your career and how you came to be working in the building materials industry?
2. **Building materials industry:** Can you please provide us with an overview of the structure of the building materials industry and the place of your company in this industry? We are particularly interested to learn more about:
 - a. Nature and level of competition of your company in the building materials industry.
 - b. Main characteristics of supply chains for raw materials (inputs) and manufactured materials (outputs).
 - c. Your company's adoption/support for industry research and innovation in building materials production and distribution.
 - d. Re-engineering of existing production processes aimed at reducing the carbon intensity of finished materials.
 - e. Nature and terms of finance for investment in the building materials industry and your company in particular.
 - f. Estimates of the destination of building materials across the residential, commercial and infrastructure sectors.
 - g. Global trade in raw materials and manufactured outputs in the building materials industry and the drivers of this trade.
3. **Climate change and built-environment decarbonisation:** Can you please provide us with an overview of how your company, in the context of the broader building materials industry, is responding to challenges seeking to reduce carbon emissions in the manufacture, distribution and use of building materials? We are particularly interested to learn more about:
 - a. Strategic planning processes being used by your company and other companies to decarbonise building materials production and distribution.

- b. New workforce requirements including new types of jobs, skill development and retraining of workers at different levels.
 - c. Measurement systems that have been developed and applied to tracking and quantifying carbon budgets in building materials production and distribution.
 - d. Uptake and use of certification systems that purchasers/consumers use to assess products and guide their choice of products.
 - e. The leakage of a proportion of new building materials into waste streams including into landfill.
 - f. Constraints experienced by building materials companies seeking to increase their efforts to decarbonise building materials production and distribution.
 - g. Consideration given to the concept of 'producer responsibility' for recovery and reuse of materials produced generated by renovation and deconstruction.
4. **Industry change:** Can you please provide us with an overview of the main sources of guidance and pressure on the building materials industry, in Australia and globally, to decarbonise materials production and distribution, especially in the housing sector? We are particularly interested to learn more about:
- h. Role of industry peak organisations or associations that your company belongs to as a member.
 - i. Recent developments in regulatory requirements in Australia and other jurisdictions, especially Europe, North America and the UK.
 - j. Forms of industry assistance in Australia and globally, such as tax concessions and grants, that encourage building materials companies to decarbonise.
 - k. Demand-side preferences of consumers, including government procurement, requiring less carbon-intensive production and distribution of materials.
 - l. New investor and insurer requirements requiring decarbonisation embedded in lending and equity terms and conditions.
5. **Future built-environment decarbonisation:** Can you please provide us with an assessment of the path that will be followed by your company and others in the building materials industry as they seek to decarbonise their production and distribution systems? We are particularly interested to learn more about:
- m. Views about how some products are more amenable to decarbonisation and how this will shape built-environment materials choices and preferences.
 - n. Anticipating pressures for accelerating built-environment decarbonisation including from regulators, investors and consumers.
 - o. Future development and extension of the 'producer responsibility' concept and practices for building materials conservation and reuse.
 - p. Future job design, skill development and retraining required for designing, specifying and constructing less carbon-intensive buildings.

Appendix 3: Industry 4.0 digital technologies that could help transform the built environment

Digital technology	What is it?	Example in the built environment
Additive and robotic manufacturing	Additive manufacturing is 3D printing, and robotic manufacturing is robots doing the jobs of humans (Çetin, De Wolf et al. 2021)	3D printing of buildings to reduce cost, time, accidents and pollution (Sakin & Kiroglu 2017)
Artificial intelligence	Computers or machines mimicking capabilities of the human mind (Maddox, Rumsfeld et al. 2019)	Using AI to provide evidence for people-centred architectural design (Bhatt, Suchan et al. 2016)
Big Data, and analytics	Large datasets that can only be handled by certain software tools (AI Nuaimi, AI Neyadi et al. 2015)	Using phone signals on the streets to understand walking patterns for design of sustainable built environments (Kim and Chanchlani 2018)
Blockchain technology	A distributed peer-to-peer system that is cryptographically secured (Çetin, De Wolf et al. 2021)	Can provide full material and energy traceability to make predictions for the recycling and reuse of materials (Shojaei, Ketabi et al. 2021)
Building information modelling	The digital representation of built asset (Charef and Emmitt 2021)	Can facilitate the selection of sustainable materials, reduce wastage and enhance project efficiency and productivity (Olawumi and Chan 2019)
Digital platforms	A software-based system providing core functionalities and a multi-sided network (Asadullah 2018)	A platform that connect physical building components with virtual components through radio frequency identification, allowing designers to explore material reuse (Xing, Pyung Kim et al. 2020)
Digital twins	Provide a virtual replica of the physical world (Çetin, De Wolf et al. 2021)	Allow for participatory and collaborative processes to empower citizens in the design of their cities (Dembski, Wössner et al. 2020)
Geographical information system	Store and process geographic information about locations (Chang 2016)	Identify locations for new cycling infrastructure (Larsen, Patterson et al. 2013)
Material passports and databanks	Digitally registered datasets of an object describing its characteristics, location, history and ownership status (Çetin, De Wolf et al. 2021)	Material passports act as an inventory of all materials within the building, showing the recycling potential (Honig, Kovacic et al. 2019)
The Internet of Things	Enables information gathering, storing, and transmitting (Li, Foliente et al. 2014)	Can help with building tracking, monitoring, control and optimisation (Ingemarsdotter, Jamsin et al. 2019)

Appendix 4: Tier-1 industries supplying materials and services to residential builders

Wooden structural component manufacturing	Structural metal product manufacturing
Fabricated wood manufacturing	Sheet metal product manufacturing
Carpentry and joinery timber manufacturing	Structural steel fabricating
Carpentry services	Machinery and scaffolding rental
Plastering and ceiling services	Plumbing services
Ready-mixed concrete services	Plumbing goods wholesaling
Painting and decorating services	Roofing services
Clay brick manufacturing	Electrical services
Structural steel erection services	Hardware wholesaling
Landscaping services	Surveying and mapping services
Tiling and carpeting services	Architectural services
Advertising agencies	Engineering consulting
Construction machinery and operator hire	Machinery and scaffolding rental
Solid waste collection services	

Source: (Kelly 2022a; 2022b)



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