SPECIAL REPORT

# Low Emissions Manufacturing: Australia's Opportunities

March 2022

# Contents

**About L.E.K. Consulting**
We're L.E.K. Consulting, a global strategy consultancy working with business leaders to seize competitive advantage and amplify growth. Our insights are catalysts that reshape the trajectory of our clients' businesses, uncovering opportunities and empowering them to master their moments of truth. Since 1983, our worldwide practice — spanning the Americas, Asia Pacific, and Europe — has guided leaders across all industries, from global corporations to emerging entrepreneurial businesses and private equity investors. Looking for more? Visit **www.lek.com.**

**About Manufacturing Australia**
Manufacturing Australia (MA) is a CEO-led coalition of Australia's largest manufacturers. MA works with governments to help Australia's manufacturing sector realise its potential. MA proposes and supports practical policy measures to ensure Australian manufacturing remains internationally competitive.

MA does not support protectionism and believes that manufacturers should be wholly accountable for their own performance. Having overcome a myriad of external economic challenges in recent years, MA members continue to operate at scale because they are efficient, well-managed and innovative businesses that have restructured and retooled to improve productivity and remain competitive.

Manufacturing is the value-adding life-blood of a balanced Australian economy. Through downstream wealth creation, research and development, import replacement and maximising the value of our natural resources, manufacturing delivers a substantial economic, social and cultural return to the nation.

Almost one million Australians work in manufacturing. Competitive manufacturing brings with it skilled direct and indirect employment, innovation and thriving local communities.

# Introduction

Australia has a significant opportunity to create and retain high-quality jobs, grow its manufacturing sector and reshore capabilities lost to imports, through a carefully managed transition to low emissions manufacturing.

Doing so is fundamentally in the national interest.

Low emissions manufacturing investment is particularly important in an Australian context: it will help to balance the Australian economy and offset some of the uncertainty facing Australia's largest resources exports in an emissions-constrained world.

The opportunity is real because of Australia's potential for natural and enduring competitive advantages in clean energy resources, technologies and capabilities, alongside its strengths in energy-intensive manufacturing industries. Leveraging one to enable the other is essential.

Manufacturing Australia has partnered with the global strategy firm L.E.K. Consulting to create this perspectives paper, examining two separate but related topics; these sections can be read independently or together:

1. The economic, social and strategic importance of Australia's manufacturing capabilities
2. The opportunities and challenges of decarbonising Australian manufacturing

We have chosen to examine these two issues in tandem because they are inherently linked and will become increasingly so in the decades to come. They also speak directly to the commercial insights, industry expertise and perspectives of those with long-standing experience and assets in Australia.

This paper explores these issues in the context of the strong belief held by Manufacturing Australia and L.E.K. Consulting that:

- Global temperatures are increasing, and emissions caused by humans are a major reason for this
- All individuals, companies and nations have a responsibility to take action to reduce emissions and mitigate the impacts of increased global temperatures

Several of Australia's globally competitive manufacturing industries and supply chains are emissions or energy intensive. If Australia's transition to a low emissions economy is achieved in part through losing manufacturing capabilities, it will be a hollow victory.

Indeed, the skills, capabilities, infrastructure, research & development (R&D) and technologies we associate with manufacturing are the very things Australia will need both during and beyond its transition to a low emissions economy.

This paper is intended to provide a readily accessible evidence base to assist policymakers, industry and interested members of the public to form views on how Australia can make a successful transition to a low emissions economy, and to show why maintaining and growing Australia's manufacturing capabilities through that transition is important to the nation's longer-term economic sovereignty and security.

Our research makes the following key findings.

1. **Manufacturing's economic and social contribution is overwhelmingly good for Australia.**
    - Manufacturing directly and indirectly employs 1.3 million Australians, with 84% employed on a full-time basis, 69% higher than the national average
    - Manufacturing accounts for more than 27% of Australia's total business expenditure on R&D
    - Manufacturing contributed $108 billion, or 5.6% of Australia's gross domestic product (GDP), in financial year (FY) 2020
    - Manufacturing exports totalled $83 billion in FY2019, or 22% of all Australian exports
    - Modern manufacturing jobs are increasingly in semi-skilled to highly skilled professions, providing long-term, stable career opportunities that are highly prized in advanced economies around the world
2. **Low emissions manufacturing technologies are real and provide viable pathways to 'net zero by 2050'.**
    - Direct electrification using clean energy; green hydrogen for use as a process feedstock; green hydrogen for use in process heating; and carbon capture, usage and storage are key long-term pathways
    - A successful transition that delivers globally competitive Australian energy inputs not only secures today's c.1.3 million direct and indirect manufacturing jobs but could also create c.100,000 new, high-quality manufacturing jobs
    - In the medium term, material reductions in emissions will be achieved through substitution of emissions-intensive inputs, process changes and efficiency improvements to existing assets
    - Australian manufacturers are already making significant investments in technologies that will reduce their emissions in the short, medium and long term
    - In some manufacturing industries, Australia will be a first mover in trialling and scaling low emissions technologies, while in others Australia will most likely be a 'fast follower' of global breakthroughs
3. **However, decarbonising manufacturing is complex and expensive.**
    - Delivered energy costs must be materially lower than current levels

if Australia is to realise opportunities for low emissions manufacturing

- Substantial investment is required in clean energy generation, infrastructure, firming and storage to meet demand from electrified manufacturing processes and hydrogen production
- Many low emissions manufacturing technologies are in their infancy and will take considerable time to mature and scale
- Manufacturing costs will increase to incorporate low emissions technologies, increasing costs for consumers
- Consumer willingness to pay a 'green premium' is limited, and certainly insufficient to bridge that gap; therefore, the cost of new technologies must be reduced towards parity with existing technologies
- Impacted manufacturing industries are typically trade exposed with low barriers to imports, presenting considerable risk to Australia's manufacturing competitiveness during transition if costs increase for the sector and higher emissions production can be imported

4. **Government policy has a vital role in de-risking, enabling and coordinating emissions reduction.** Policies should address four priority challenges, namely:

   - **Reduce the delivered cost of clean energy:** Significant investment in clean energy generation, firming and infrastructure is needed to deliver lower-cost clean energy necessary to underpin low emissions manufacturing. Direct government investment and policies to 'de-risk' investment in clean energy generation, firming, storage and infrastructure projects are required
   - **Scale the breakthrough technologies:** Proving, scaling and reducing the costs of low emissions manufacturing technologies, including Carbon Capture and Storage (CCS), through co-investment in R&D and financial incentives to trial and scale new technologies
   - **Stimulate 'green manufacturing' demand:** Stimulating demand for low emissions products through consistent national standards and accreditation developed in partnership with industry, and changes to government procurement
   - **Level the playing field:** Incentives and regulations to de-risk investment in low emissions manufacturing for businesses that compete with imports from higher emissions plants overseas

This paper includes four chapters about specific manufacturing industries in Australia: steel, aluminium and alumina, cement and concrete, and ammonia. These chapters set out key information about the industrial processes, local context, emissions reduction pathways, and future competitiveness for these industries and value chains.

The contributions to Australia of these manufacturing industries, and the broad industrial ecosystems they support, are significant. So too are these industries' carbon emissions. For Australia to retain the benefits that flow from manufacturing and for the world to realise the benefits from significant emissions reduction, it is important that these industries remain competitive through Australia's transition to a low emissions economy.

The only economically sustainable way to effect a transition to a low carbon economy is to drive down the costs of low emissions technologies to a point where they are cost competitive with today's inputs.

This will not be easily achieved, and it is important to acknowledge that:

- Australian manufacturers often produce products with low emissions by global standards
- The policies and aspirations for, approaches to, and rates of emissions reduction will vary by country and region, and Australian manufacturers will not be competitive if they face disproportionate costs
- Current evidence that consumers and industry are willing to pay 'green premiums' for any increased costs associated with low emissions products, particularly for commodities, is weak
- Some necessary technologies are not yet proven or commercial, particularly at the scale required to meet the demands of a modern world
- Stable, long-term emissions policy that is broadly consistent between jurisdictions and that takes into account investment horizons and capital cycles is necessary to provide a confident landscape for low emissions manufacturing investment

Despite these challenges, Australia has a unique and compelling opportunity to become a world leader in several low emissions manufacturing industries.

By leveraging its competitive advantages in clean energy resources, technologies and capabilities, alongside its strengths in energy-intensive manufacturing industries, Australia can retain and grow its manufacturing capabilities while reducing emissions on a pathway to net zero emissions by 2050.

## Manufacturing in Australia Snapshot

Australia's manufacturing sector includes a diverse range of businesses that produce outputs including metals, building materials, chemicals, textiles, food products and machinery

**$108 billion** contributed to the national economy by the manufacturing sector, representing **5.6% of GDP** in FY20

**$83 billion** worth of manufacturing merchandise exported in FY19-22% of all Australian exports – and attracted $130 billion of foreign investment in Australia

**1.1% p.a.** reduction in the emissions intensity of Australian manufacturing since 1990, delivering almost **30% less C02e per dollar** of real GDP contributions over this period

**$4.5 billion on R&D** was spent by the manufacturing industry in FY18, 27% of Australia's total R&D spend. It employs **19,000** full-time equivalent staff engaged in research

**c.2%** of all Australian patents between 2010-21 were awarded to Manufacturing Australia's members

**890,000** jobs are supported by the manufacturing industry, of which **84%** are employed on a full time basis, **69% higher** than the national average

# Executive summary

Manufacturing Australia has partnered with the global strategy firm L.E.K. Consulting to create this perspectives paper, which is designed to provide a readily accessible evidence base about Australian manufacturing and the challenges and opportunities of decarbonisation.

This perspectives paper has been designed to assist policymakers, industry and interested members of the public to form views on how Australia can make a successful transition to a low emissions economy while retaining and growing its manufacturing sector and the broad benefits that it provides to the nation. The paper examines two separate but inherently related topics; these sections can be read independently or together:

1. **The economic, social and strategic importance of Australia's manufacturing capabilities** — demonstrating that manufacturing capabilities are overwhelmingly good for Australia's economy and society
2. **The opportunities and challenges of decarbonising Australian manufacturing** — demonstrating that low emissions manufacturing technologies are real and provide viable pathways to 'net zero by 2050'

Together, these show that there are significant opportunities for Australia in a transition to low emissions manufacturing — if Australia can provide globally competitive energy inputs, a transition to low emissions manufacturing will not only secure today's c.1.3 million direct and indirect manufacturing jobs but potentially create c.100,000 new, high-quality manufacturing jobs. This is in line with experience from the US 'manufacturing renaissance', which was enabled by competitive energy inputs becoming available from around 2010.

### I. Manufacturing capabilities provide significant benefits for Australia

It is important, at the outset, to consider the significant economic and social benefits that flow from having a robust manufacturing sector.

- Manufacturing contributed 5.6% of GDP in FY2019-2020, representing over $108 billion of annual gross value to the Australian economy, amongst other important contributions
- Manufacturing accounted for $83 billion of exports in FY2019 (22% of Australia's merchandise exports)
- Australian manufacturers employed 890,000 people as of February 2021 and has been broadly steady since 2015
- Manufacturing is often a linchpin employer in regional areas
- Australian manufacturers spent the greatest portion of sectoral GDP contribution on R&D out of any sector in FY2018, with their R&D spend of $4.5 billion representing c.27% of total Australian R&D spend that year

- Manufacturing enables valuable skills and investments throughout the value chain, from R&D to marketing and digital
- Manufacturing is an important sovereign capability; for example, Australia was able to reduce its reliance on international supply chains in the face of disruptions from COVID-19
- Manufacturing is an ecosystem that supports extensive linkages with other sectors
- Manufacturers are large industrial users of energy, providing stable demand along with flexibility to quickly reduce load to provide stability to national power grids during periods of high demand
- Australian manufacturing closes the loop for the circular economy and benefits the environment
- Australian manufacturing enables high standards of environmental and consumer protection.

Larger manufacturing businesses, although few in number, are particularly important to the realisation of these benefits for Australia, accounting for more than a third of employment in the sector.

### II. Low emissions manufacturing technologies are real and provide viable pathways to 'net zero by 2050'

- There are credible emissions reduction pathways for manufacturing sectors
- These technologies are in varying stages, some decades away from commercialisation
- A phased transition will be necessary while these pathways become viable

There are credible emissions reduction pathways for almost all the carbon emissions generated by the Australian manufacturing sector.

In the long-term, a significant proportion of those emissions will most likely be abated through direct electrification using clean energy, green hydrogen for use as a process feedstock, green hydrogen for use in process heating, and carbon capture, usage and storage. The emissions reduction pathways for each focus manufacturing sector (steel, aluminium and alumina, ammonia, and cement and concrete) are summarised in Table 1 below, with further detail included in the sectoral analysis chapters of this report.

While these technologies exist, they are in various stages of technical and commercial development in Australia and around the world, with some still decades away from likely commercialisation at scale.

The Australian Government's Technology Investment Roadmap identifies several key technologies that will be necessary for Australia to retain its manufacturing capabilities in a low emissions economy. The technologies identified by the road map broadly align to the emissions reduction pathways identified in this paper for these focus sectors. However, more ambitious (lower) cost targets for the technologies will be needed to enable competitiveness of Australian manufacturing.

Australia's major manufacturers have started developing and scaling those medium-term technologies where it is possible to do so, while contributing to

**Table 1**
Summary of emissions reduction pathways by focus sector

| Vertical | Steel | Aluminium and alumina | Ammonia | Cement |
|---|---|---|---|---|
| **Australian context** | • Two primary crude steel production plants<br>• Accounts for less than 1% of global steel production | • Four primary aluminium smelters<br>• Largest bauxite producer in the world and second-largest producer of alumina<br>• Sixth-largest producer of aluminium | • Seven ammonia plants<br>• Represents less than 1.5% of global ammonia production | • Five integrated cement manufacturing facilities<br>• Eleven stand-alone cement mills |
| **Decarbon-isation pathway** | • Challenging — hydrogen-based direct reduced iron-electric arc furnace (DRI-EAF) most prospective technology but not yet proven or available at industrial scale | • Clear for aluminium — decarbonisation of the electricity grid<br>• Somewhat complex for alumina — multiple pathways leveraging direct electrification and green hydrogen possible | • Clear — green hydrogen is the most prospective but hasn't been proven at scale | • Complex — multiple solutions required, including a change in standards, reduction in clinker factor, fuel switching and CCS from process emissions |
| **Transition challenge — industry** | • Technology — hydrogen DRI-EAF breakthrough and commercial deployment<br>• Legacy infrastructure — blast furnace-basic oxygen furnace (BF-BOF) | • Technology for aluminium — development of non-carbon-based anodes<br>• Scale for alumina — application of existing technology, but at a scale not trialled before | • Technology — commercial deployment of hydrogen electrolysers<br>• Legacy infrastructure — steam methane reforming | • Standards development<br>• Recycled materials transport<br>• SCM supply in net zero world |
| **Transition challenge — enabling** | • Competitively priced hydrogen and supporting infrastructure<br>• Potential carbon leakage — steel imports | • Competitively priced firm renewable electricity<br>• Competitively priced hydrogen and supporting infrastructure | • Competitively priced energy — gas and/or firm renewable electricity<br>• Third-party CO2 distribution and storage infrastructure<br>• Potential carbon leakage — ammonia imports | • Competitively priced energy — gas and/or firm renewable electricity<br>• Third-party CO2 distribution and storage infrastructure<br>• Potential carbon leakage — clinker/cement imports |
| **Further detail** | Page 43 | Page 55 | Page 67 | Page 80 |

Source: L.E.K. Industrial Net Zero model. See sectoral analysis for further information.

local and global R&D programmes working towards long-term decarbonisation.

Examples of existing efforts by Australian manufacturers that have reduced emissions and near-term projects to reduce emissions are included in Table 2 below.

### III. Decarbonising manufacturing is complex and expensive

- Developing and scaling low emissions manufacturing technologies will take time
- Using low emissions manufacturing technologies will increase costs to consumers
- Significant infrastructure investment is required
- A level playing field will be needed for impacted trade-exposed manufacturing sectors

For many sectors in the Australian economy, the pathway to reduce emissions is relatively straightforward and hinges on technologies and transition in the electricity and transport sectors.

**Table 2**
Examples of short and medium-term emissions reduction projects

| Vertical | Steel | Aluminium and alumina | Ammonia | Cement |
|---|---|---|---|---|
| **Short term response for emissions reduction** | • The Turbo Alternator Project at Port Kembla uses excess by-product fuels to generate electricity and has saved 211 kt CO2e since 2019<br>• The Finlay PPA covers purchase of 233,000 MWh of energy per annum from the Finlay Solar Farm, and covers 20% of BlueScope's electricity purchases | • Commercialisation of inert anodes for primary aluminium production is expected to reduce process emissions from 1.6t CO2/tonne of aluminium to less than 0.01t CO2/tonne aluminium<br>• Investments in mechanical vapour recompression (MVR), concentrating solar thermal (CST), and fuel switching to reduce emissions associated with bauxite digestion and alumina calcination<br>• A partnership between Rio Tino and ARENA for a $1.2 million hydrogen feasibility study | • IPL invested $2.97m in a hydrogen feasibility study for its Dyno Nobel Moranbah facility in Queensland, including $980k of funding provided by ARENA<br>• Energy and resource efficiency is providing incremental reductions in emissions intensity | • Use of SCMs including blast furnace slag, fly ash and silica fume can reduce the emissions intensity of cement, with 1Mt replaced Portland cement saving 0.67-1 Mt CO2e p.a.<br>• Use of alternative fuels such as wood waste/biomass, solvents, carbon powders, used oil and spent pot liners reduces emissions; approximately 18% of total energy requirement in Australian cement is met by alternative fuels with lower emissions profiles than coal |
| **Further detail** | Page 51 | Page 60 | Page 76 | Page 88 |

Manufacturing is different. The production processes for products that underpin our modern economy often result in 'scope 1' emissions through processes that are not yet ready for conversion to a renewable-based approach, or as a result of the underlying and unchangeable chemistry of the process. In some instances, today's renewable energy sources, like electricity generation from solar or wind, cannot be directly used to meet the energy (often high heat) requirements of a process.

The enabling technologies and pathways to decarbonise different manufacturing segments vary, and there are important contextual differences for each manufacturing segment between Australia and other economies that must be considered. For this reason, this paper has profiled four key manufacturing segments and identified the most prospective pathways to reach net zero emissions for each of the following:

- Steel
- Aluminium and alumina
- Ammonia
- Cement and concrete

While each of these focus sectors has its unique opportunities and challenges, there are consistent themes, which are borne out in this report:

1. **Zero emissions manufacturing technologies exist but will take time to develop, mature and scale.** In some cases, these technologies are yet to be demonstrated at a commercial scale commensurate with the requirements of the manufacturing sector (e.g. electrolysis for green hydrogen), while others require more fundamental technical breakthroughs and practical demonstration that will need Australia to contribute to global efforts rather than expect to make breakthroughs on its own.
2. **Costs will increase to utilise zero-emissions manufacturing technologies** — often as a result of the renewable energy input requirements — and further challenge the competitiveness of Australian manufacturing due to the fact that *Australia already has high energy prices by global standards*.
3. **Significant infrastructure and investment are required**, both to adapt manufacturing production processes and to provide for increased renewable energy or other abatement needs at manufacturing locations.
4. **Impacted manufacturing sectors are trade exposed, and Australia will need to account for the different approaches to emissions reduction in competitor countries.** Typically, competitors for Australian manufacturers are **not** located in the EU or the US, where more aggressive emissions reduction policies are in place. Australia must avoid offshoring emissions-intensive activities to countries with lower standards for zero net environmental gain.

These themes are explored further below in order to understand the policy implications

**Figure 1**
Steps to decarbonise the Australian Manufacturing Industry

| | ENHANCE | BRIDGE | BREAKTHROUGH |
|---|---|---|---|
| **Action by industry** | • Maintaining and strengthening existing actions to decarbonise manufacturing processes using existing infrastructure<br>• Identifying most prospective technologies and pathways to deliver zero emissions<br>• Setting ambitious but achievable targets<br>Examples<br>• Reducing cement needed in concrete using supplementary cementitious materials (SCMs)<br>• Capturing CO2 from ammonia production for use in food & beverage manufacturing<br>• Reducing energy consumption in steel production by utilising waste gases | • Meeting market demand and maintaining competitiveness through applying and scaling new clean technologies<br>• Delivering technically and economically feasible emissions reduction<br>Examples<br>• Partially replacing hydrogen from natural gas with green hydrogen in ammonia production<br>• Applying inert anodes for aluminium smelting to eliminate Scope 1 emissions<br>• Developing mechanical vapour compression to replace fossil fuels used in bauxite digestion for alumina production | • Developing and investing in new decarbonisation technologies requiring major breakthroughs globally in technology or scale<br>• Investing for a clean and competitive Australian manufacturing future<br>Examples<br>• Providing high volumes of reliable, internationally competitive renewable energy for 24/7 aluminium smelting<br>• Proving technical and commercial viability of scale green hydrogen production<br>• Proving technical and commercial viability of direct reduced iron (DRI) using green hydrogen for steel production |
| **Enablement required** | • Consistent and stable long term emissions reduction policy<br>• Reliable and globally cost competitive energy inputs<br>• Long term energy, hydrogen and CCUS infrastructure planning and provision | • Level playing field for Emissions-Intensive and Trade-Exposed (EITE) manufacturing<br>• Financial support to reduce cost and scale emission reduction technologies<br>• Policies and incentives to stimulate demand for low carbon products (including information & education and standards) | • Desire and action to maintain domestic manufacturing capability<br>• Financial support for Research & Development<br>• Internationally competitive environment for long-term investment |

that these findings present for maintaining and growing Australian manufacturing through a transition to a low emissions economy.

## IV. Australia must convert its clean energy advantage into a clean manufacturing advantage

- Australian energy costs have increased substantially over the past decade
- Delivered costs of clean electricity must be much lower to enable low emissions manufacturing
- Direct government investment and policies to 'de-risk' investments in firming, storage and transmission of clean electricity are a key 'lever' to enable low emissions manufacturing
- If Australia can regain globally competitive energy inputs, it could secure today's manufacturing jobs and create ~100,000 new high-quality manufacturing jobs

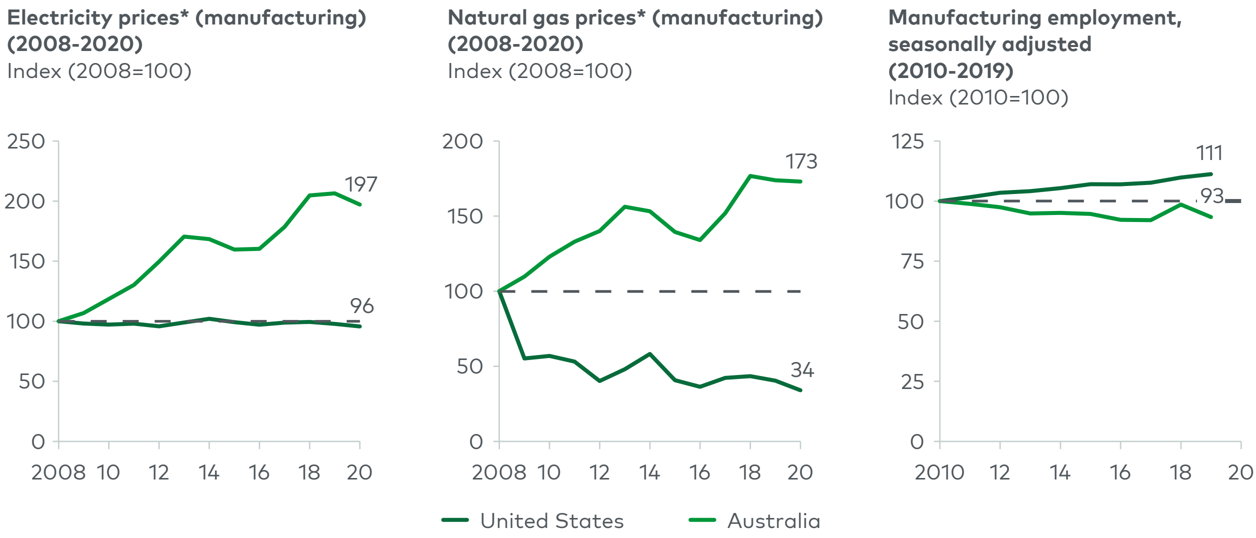
Competitive energy inputs underpin and enable competitive manufacturing. Over the longer term, Australia has a number of natural competitive advantages that support it as a future world leader in no/low emissions energy production. These include large existing solar and wind resources, space available to create and scale these renewable assets, and proximity to countries where demand for energy is forecast to be high and growing (specifically Asia). If we can leverage this potential and provide globally competitive energy inputs, we can create a 'manufacturing renaissance' in Australia — we have seen this happen before in the US, delivering a step change in manufacturing jobs and investment.

As shown below in Figure 2, Australian energy costs have increased substantially over the past decade, hindering the competitiveness of Australian industry. Australian manufacturers in 2020 paid an estimated 73% more for gas and 97% more for electricity than they did in 2008. While substantial cost increases are clear, Australian energy markets are also creating challenges for industry through increasingly frequent supply interruptions, sharper and more frequent price spikes that require load shedding, and reduced options for long-term supply.

In contrast, recent experience in the United States demonstrates how an energy advantage can bring growth to the manufacturing sector and in turn the broader economy. Since the early 2000s, the United States has witnessed a significant decline in natural gas prices. Manufacturers in the United States in 2020 paid, on average, 66% less for

**Figure 2**

Electricity and natural gas price comparison and manufacturing employment between Australia and the United States* (2008-2020)



**Electricity prices* (manufacturing) (2008-2020)**
Index (2008=100)

**Natural gas prices* (manufacturing) (2008-2020)**
Index (2008=100)

**Manufacturing employment, seasonally adjusted (2010-2019)**
Index (2010=100)

*Indexed real electricity and natural gas average annual price. Values differ from United States Studies Centre analysis (2018) due to different index reference base.

Source: Australian Bureau of Statistics, 6427.0: Producer Price Indexes, Input to the manufacturing industries; US Energy Information Administration, Natural gas and electricity industrial prices; US Bureau of Labor Statistics, All Employees, Manufacturing [MANEMP], Current Employment Statistics (Establishment Survey); Australian Bureau of Statistics, Labour Force, 6291.0.55.003: Detailed, Quarterly Employed persons by industry division of main job (ANZSIC) natural gas than they did in 2008. In response, investment in the sector resulted in 11% growth in total employment for the US manufacturing sector between 2010 and 2019 (the final years of data pre-COVID-19), while employment in the Australian manufacturing sector was flat.

Competitive energy intersecting with Australia's renewable energy advantage could become a key input into a healthy future manufacturing sector, but also provide an opportunity to diversify its export economy towards renewable and tradeable energy sources and value-added, low emissions manufactured products.

If Australia can globally provide competitive energy inputs, a transition to low emissions manufacturing presents a significant prize for the country — not only would it secure today's c.1.3 million direct and indirect manufacturing jobs, but it could also create c.100,000 new, high-quality manufacturing jobs. This is in line with experience from the US 'manufacturing renaissance', which was enabled by competitive energy inputs becoming available from around 2010 through shale gas.

Success will require Australia to both decarbonise and reduce the cost of energy inputs. Analysis below shows that an Australian manufacturing renaissance delivering jobs and investment will not happen with delivered electricity costs of $70 or $80 per MWh — the competitive disadvantage for Australian manufacturing is simply too great in a world that will decarbonise at different rates.

### V. Key emissions reduction pathways require further technological development and will increase costs for Australian manufacturers

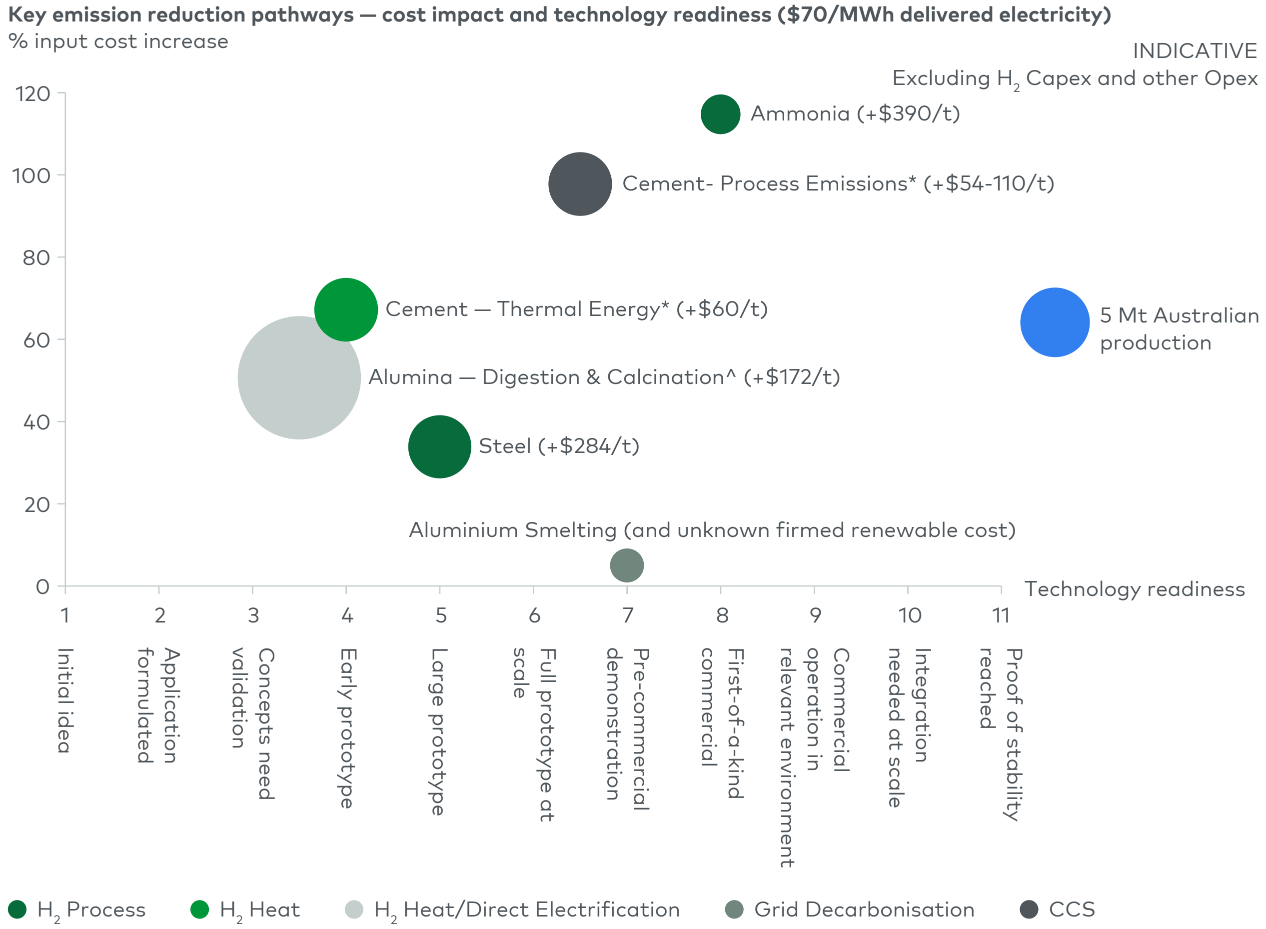
Four key emissions reduction pathways for the manufacturing sector are:

- Production of green hydrogen for use as a process feedstock — this is applicable to steel and ammonia production
- Production of green hydrogen for use in process heating — this is applicable for alumina and cement production
- Direct electrification from renewable sources — this is applicable to alumina production and aluminium production, along with many other manufacturing applications
- Carbon capture, usage and storage — this is applicable to steel, ammonia and cement production

Each will require further technological development and capital expenditure in order for the requisite sectors to implement these pathways for emissions abatement.

Figure 3 shows the operating economics and readiness of net zero technologies. It is clear the impact on each focus industry varies according to existing processes and inputs. All emissions reduction pathways are at early levels of technology readiness (at best 'first of a kind' commercial) and will result in significant increases in commodity costs (from c.30% increases to more than doubling), given Australia's current energy costs.

**Figure 3**
Emissions reduction pathways — cost increases and technology readiness by focus sector at $70/MWh delivered electricity



*Cement cost increases will result from both thermal energy and process emissions cumulatively, and cement thermal cost increases are a 'best case' based on East Coast gas rather than coal; ^Alumina digestion and calcination are combined given similar technology readiness, and are a 'best case' based on digestion and calcination using West Coast gas rather than coal. Analysis as at July 2021

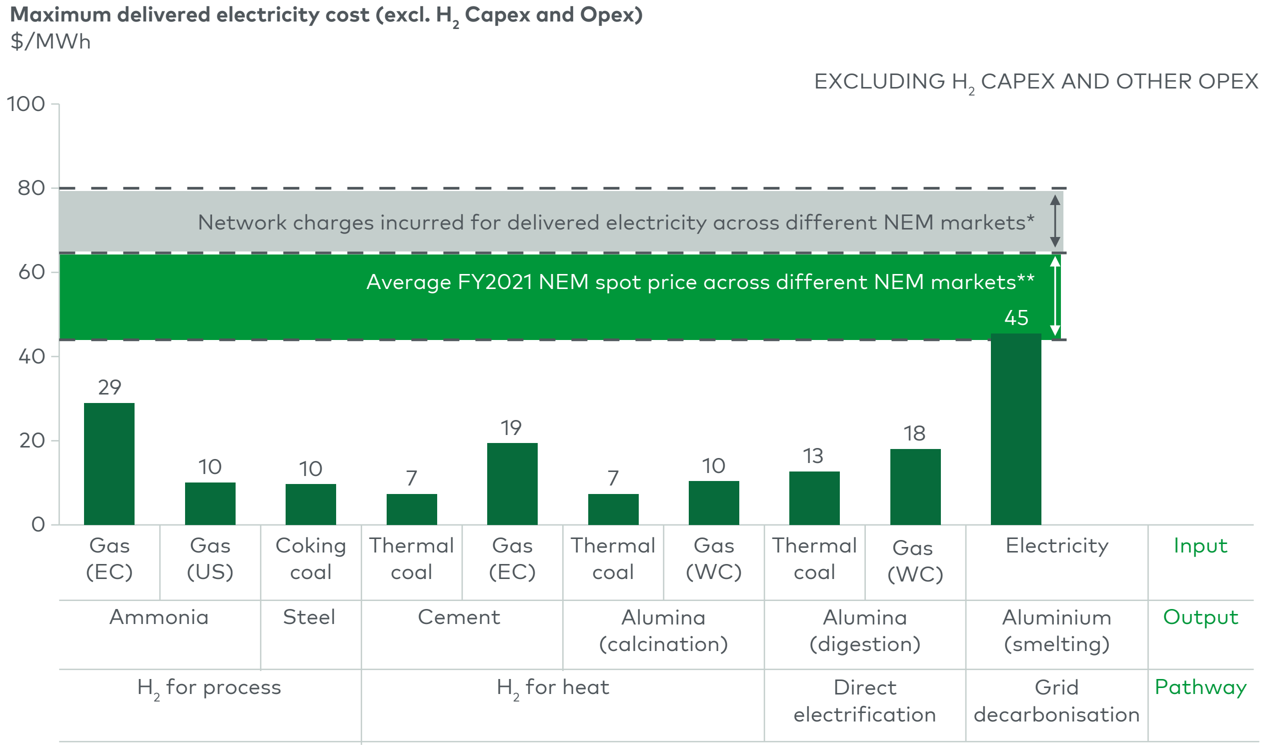
Source: IEA; L.E.K. Industrial Net Zero model

Technological development for each pathway alone will not mitigate the cost impact of emissions reduction. The cost of delivered electricity also needs to be far below current levels for these pathways to be cost competitive against current higher emissions production.

Figure 4 shows the required electricity prices necessary for each new pathway to regain cost equivalence with existing technologies. This scenario only includes electricity costs for the pathways and ignores the significant new capital investment that will be required to adapt plants, hydrogen, and electricity generation and distribution networks. It is clear that reduced delivered electricity costs have a critical role to play in improving the competitiveness of clean manufacturing technologies.

**Figure 4**

Required delivered electricity prices for input cost parity against higher emissions inputs (excluding $H_2$ CAPEX and OPEX)*



Note: Natural gas prices for Australia West Coast (WC), Australia East Coast (EC), United States (US);
* Network charges includes distribution tariffs (DUOS), transmission tariffs (TUOS) and jurisdiction tariffs (JUOS) for high voltage industrial users for peak, shoulder and off-peak usage; ** Average FY21 spot prices in the NEM ranged from $43.69 (TAS) to $64.81 (NSW)

Source: L.E.K. Industrial Net Zero model

This 'best case' view of cost competitiveness needs to be considered within the context of current high Australian energy costs and uncertainty about the pathway to cost-competitive firmed renewables. For instance, the analysis in Figure 4 is comparing against typical East Coast gas prices of $8/GJ, which are high compared to other countries; excludes **any** cost for investment in electrolysers to make green hydrogen; and assumes that hydrogen can be produced at the manufacturing plant using electrolysers achieving the world-best demonstrated efficiency of 67% of maximum theoretical efficiency, with no additional costs for hydrogen transportation or storage.

It also shows that the economics of renewables use in the manufacturing sector differs to the electricity sector. The analysis illustrates that fossil fuels are low cost for the manufacturing process input or energy that they provide. The challenge in manufacturing is to both address the emissions that must be reduced while also finding economic solutions for new technology and energy delivery. While there are signs renewables present a cost advantage over coal and gas for electricity generation when measured on a levelised cost of energy basis, this benefit does not translate directly to all industrial process transitions, as the demand for physical and energy inputs in new processes tends to be higher than under the current approach, which consequently results in much higher future production costs.

This delivered electricity cost challenge must be solved — a doubling of fertiliser costs (plausible when Australian ammonia costs are shown to double in Figure 4) is estimated to translate into a greater than 40% increase in food costs.[1]

Australia has competitive advantages in a supportive climate and substantial space that provides it with an opportunity to capitalise on the clean energy transition. However, the differences in demand, economics and returns to scale and in firming needs for renewable energy versus the existing energy sources demonstrate that we need to be cautious about assuming this will automatically confer a substantial competitive advantage for manufacturing in Australia.

### VI. Cement presents unique challenges and opportunities for emissions reduction

While the key emissions reduction pathways can address most of the emissions from focus manufacturing sectors, cement production poses a unique 'process emission' challenge because the calcination of limestone that is integral to the product is responsible for the majority of the emissions from the sector.

This means that some form of carbon capture or offsets will be essential for the cement industry to fully decarbonise.

However, cement also demonstrates the importance of considering emissions across the end-to-end value concrete value chain and full life cycle of products — it is possible to deliver material lifetime emissions reductions even before addressing process emissions through:

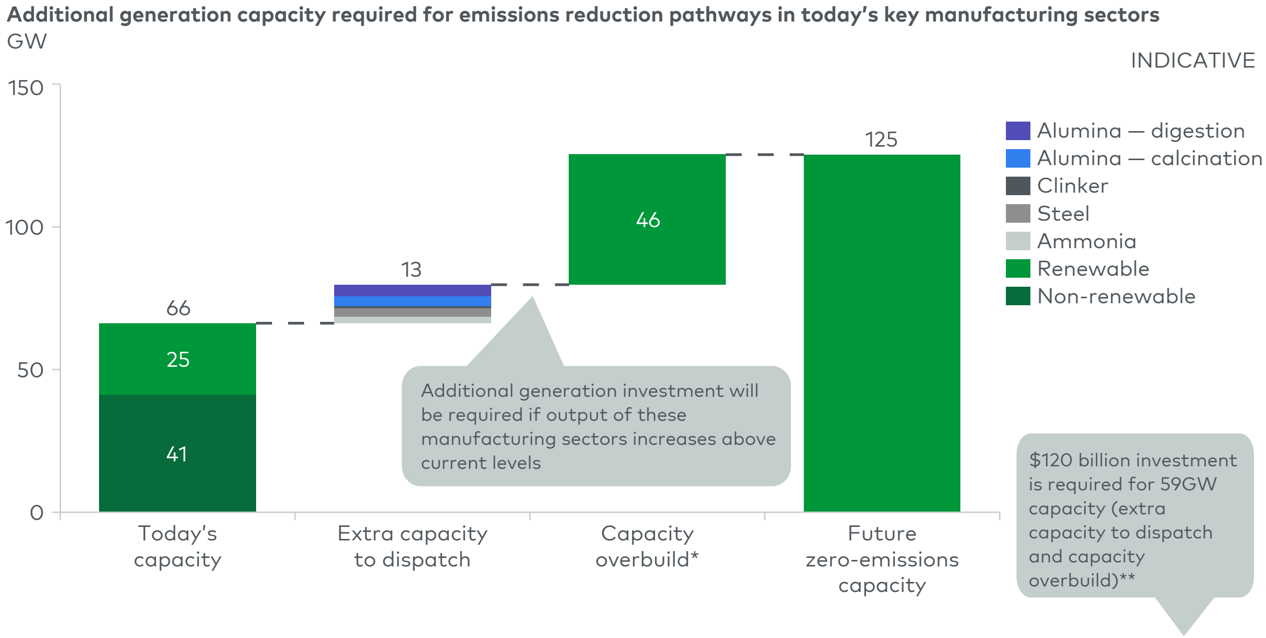
- Innovating in the design of buildings and infrastructure to reduce the intensity of concrete use
- Substituting higher proportions of recycled and alternative materials in cement and concrete to lower emissions intensity of the product that is used
- Investing in research and development (R&D) that looks to maximise the ability for concrete to deliver unique 'recarbonation' effects by absorbing carbon from the atmosphere in situ

### VII. Key emissions reduction pathways will require unprecedented investment in new renewable energy

All four of the key emissions reduction pathways (green hydrogen as a process input, green hydrogen for process heat, direct electrification and carbon capture, usage and storage) ultimately shift manufacturing from using fossil fuel inputs to using renewable electricity as the basic input, whether through direct electrification or indirectly through electrolysis of hydrogen.

The obvious implication of this is that if Australia maintains its focus on

**Figure 5**
Additional generation capacity required for emissions reduction pathways in today's key industrial sectors across NEM and SWIS*



Additional generation investment will be required if output of these manufacturing sectors increases above current levels

$120 billion investment is required for 59GW capacity (extra capacity to dispatch and capacity overbuild)**

*Today's capacity reflects capacity in the National Energy Market in Eastern Australia and the Southwest Interconnected System in Western Australia; capacity overbuild is calculated using the weighted average capacity factor for hydro, wind and solar generation in FY2021. Capacity factor is defined as a percentage of actual energy generation (MWh) relative to the maximum theoretically possible generation based on nameplate capacity (MW x 365 days x 24 hours); **Assuming the same capacity mix of wind, solar and pumped hydro based on nameplate generation capacity today using GenCost 2021 capital assumptions for wind, large-scale solar PV and pumped hydro (12 hours)

Source: AEMO; OpenNEM; GenCost 2021 (CSIRO and AEMO); L.E.K. Industrial Net Zero model

manufacturing sectors at current levels and the key emissions reduction pathways are adopted, there will be a significant increase in demand for renewable electricity in Australia.

The electricity required to apply the key emissions reductions for these sectors is estimated at a steady draw of 13GW from the network. This only assumes emissions reduction pathways for the focus manufacturing sectors and at current output levels. However, renewable generation typically provides variable output, whereas manufacturing needs are often constant (requiring firmed supply), and **must** be constant in some cases (e.g. aluminium production). If new renewable generation (solar, wind, hydro) was brought online in the same mix of renewable generation in the NEM today and achieved the same weighted average capacity factor (23% in FY2021), an incremental 46GW of new renewable generation is required to ensure that the manufacturing sector can be assured of drawing 13GW consistently to run electrolysers and electrified processes.

This would imply new renewable capacity needs to be built with more than double the entire renewable capacity that exists today across the NEM and the SWIS and, given the variable nature of generation from these renewables sources, makes storage a priority to enable reliable energy. This additional capacity does not provide for future production increases, decarbonisation of other sectors such as transport, or replacement of non-renewable electricity generation for household and commercial consumption.

Based on current levelized cost estimates for renewable generation and maintaining the current mix of renewable generation, this amount of capacity would imply investment of around $120 billion in new renewable generation alone to transition just focus manufacturing sectors — transmission and distribution network upgrades would increase the investment requirements, as would the more than 9GW of electrolysers and modifications to manufacturing facilities that would be required. What is clear is that there is an unprecedented level of investment required to enable these emissions reduction pathways across Australia and globally. However, the scale of investment to underwrite this climate transition is within the realms of our most recent COVID-19 crisis, where the direct economic and health support provided since the onset of the pandemic totalled $311 billion as at the time of the Australian Government's FY2021-2022 Budget.[2]

### VIII. The implicit abatement costs of key emissions reduction pathways are high relative to carbon taxes and offsets

An estimate of the cost of abatement per CO2 pathway can be made assuming a price for firmed, renewable electricity and accounting for the energy demand of each new process method. If the Australian manufacturing sector could purchase delivered electricity at $40/MWh,[3] the implied cost of abatement for the key pathways is still substantial. Taxes will not fix this, as shown in Figure 6.

Reduced delivered electricity prices and incentives to invest in clean technologies will be required to avoid recourse to offsets as the default. For all of the focus sectors and pathways, the implicit abatement cost is much higher than the Australian Carbon Credit Units (ACCUs), generally above the estimated carbon prices required to achieve Paris targets, and in some cases above the world's highest carbon tax, currently in place in Sweden. As per Figure 4, this assessment is the 'best case' view of cost competitiveness for the key pathways, as it assumes typical East Coast gas prices of $8/GJ, excludes **any** cost for investment in electrolysers to make green hydrogen, and assumes no additional costs for hydrogen transportation or storage.

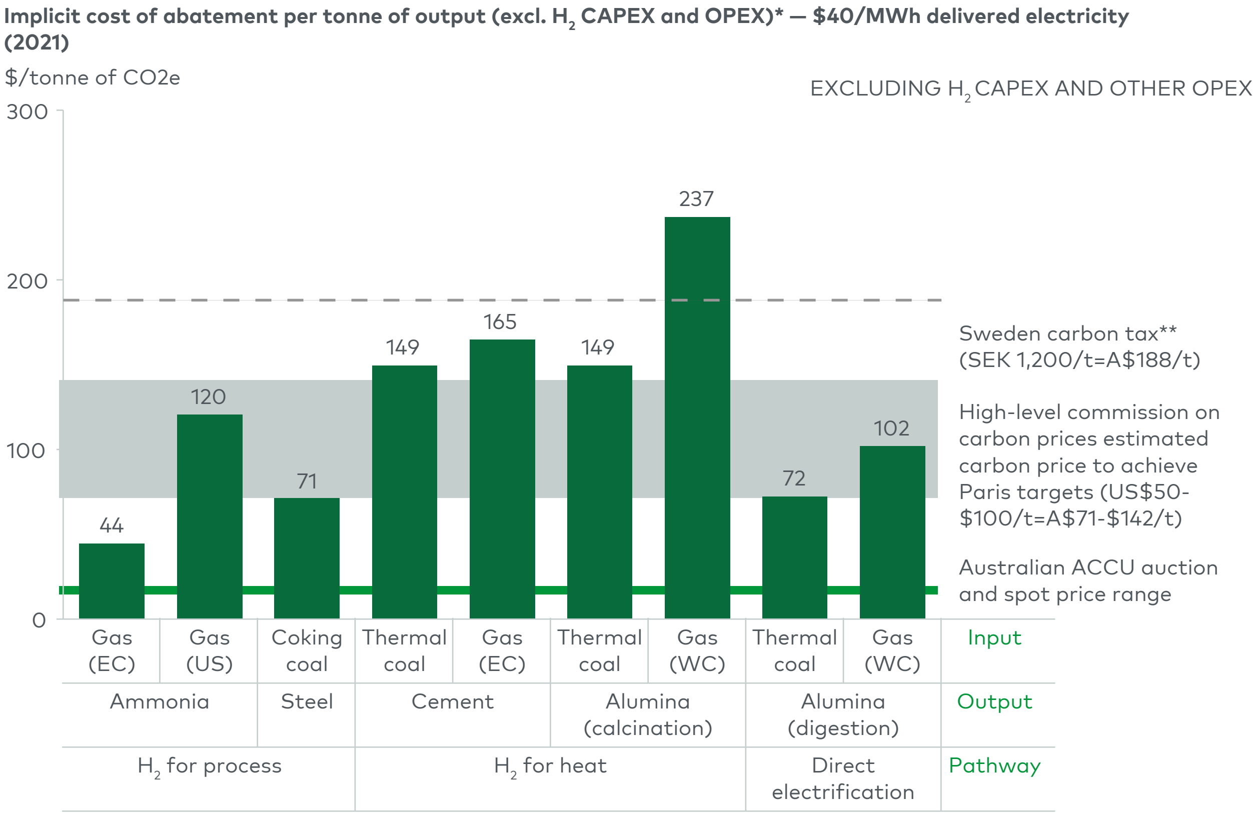
### IX. Government policy has a vital role in de-risking, enabling and coordinating emissions reduction

A successful transition will require Australian policymakers to recognise and address the following interrelated issues:

- There are credible emissions reduction pathways for almost all the carbon emissions generated by the Australian manufacturing sector, and while some of these are nearing commercialisation, others are some decades away; transitional steps will be necessary

**Figure 6**

Implicit cost of abatement per tonne of output at $40/MWh delivered electricity (and excluding $H_2$ CAPEX and other OPEX)*



*The assumed price for delivered electricity is $40/MWh — does not include any provision for CAPEX required for electrolysers or plant modification; **Sweden has the highest carbon tax in the world at SEK 1,200 (July 2021), converted using exchange rate of $6.40 AUD/SEK Analysis as of July 2021

Source: L.E.K. Industry Net Zero model; World Bank; Clean Energy Regulator Statement of Opportunities in the ACCU Market and Market Updates; IEA

- Competitive energy costs enable a vibrant manufacturing sector, and differential energy costs between Australia and other countries today and into the future dictate the competitiveness of production
- The key pathways to reduce emissions in focus manufacturing sectors will increase energy demand and input costs
- This increase in costs reflects a fundamental difference in the cost of fossil fuels and renewable inputs for manufacturing processes that technological development alone will not address
- The increased energy requirements of the key emissions reduction pathways will require unprecedented enabling investment in renewable generation, but this investment cannot come at the expense of globally competitive energy costs
- Carbon capture and use/storage technology will most likely be required for the cement industry, and there is potential for scale economies in CCS infrastructure that could make this approach an attractive alternative pathway for other manufacturing sectors and the broader economy if available

- Australian manufacturers are exposed to competitors based in countries that are pursuing different approaches to emissions reduction and moving at different speeds, challenging the cost competitiveness of Australian manufacturing
- The high implicit abatement costs of key emissions reduction pathways demonstrate that carbon pricing is unlikely to make these pathways cost competitive versus today's fossil fuel inputs
- There is currently weak evidence for 'green premiums' that reflect the difference in costs between emissions-intensive and zero-emissions products in the absence of mandates

Government policies should work in a coordinated way to target four key objectives:

1. **Scale the breakthrough technologies:** Proving, scaling and reducing the costs of low emissions manufacturing technologies, including CCS, through co-investment in R&D and financial incentives to trial and scale new technologies.
2. **Reduce the cost of clean energy:** Significant investment in clean energy generation, firming and infrastructure in order to deliver the lower-cost clean energy that underpins low emissions manufacturing.
3. **Stimulate 'green manufacturing' demand:** Stimulating demand for low emissions products through consistent national standards and accreditation developed in partnership with industry, and changes to government procurement.
4. **Level the playing field:** Incentives and regulations to de-risk investment in low emissions manufacturing for businesses that compete with imports from higher emissions plants overseas.

The solution for enabling Australia's opportunities from low emissions manufacturing will require a coherent series of policies across all three elements shown above in order to achieve the desired outcomes for Australia and the world:

- A focus on ensuring access to scalable and cost-competitive low emissions technology (enabled by lower delivered electricity costs) is the first and most technical step towards the transition, but our analysis shows that Australia will most likely still face significant escalation in the costs of products that are fundamental to our economy and society, slowing investment and transition without other action
- A focus on generating demand and pricing reflecting increased costs for low emissions products will be required to assist in the development of economic business cases for the investments required in the sector that will enable Australia's transition to a low emissions economy
- A focus on addressing differentials between Australian and global emissions reduction efforts will be required to support the competitiveness of Australian manufacturing through the

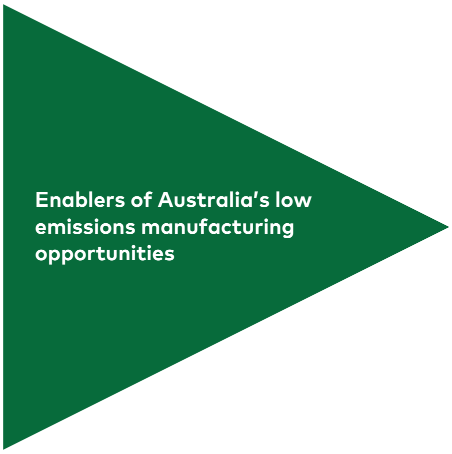
**Figure 7**

Enablers of Australia's low emissions manufacturing opportunities

**Low emissions technology cost competitiveness**

*'Scale the breakthrough technologies' and 'reduce the cost of clean energy' to address:*

- Technological development
- Increased input costs
- Infrastructure investment (energy system and CCS)



**Australian competitiveness**

*'Level the Playing Field' to address:*

- Delivery of emissions reduction
- Policy differentials
- Trade exposure and emissions leakage

**Low emission product demand and pricing**

*Stimulate 'green manufacturing' demand to address:*

- High implicit abatement costs relative to carbon prices
- Lack of green premiums

Source: L.E.K.

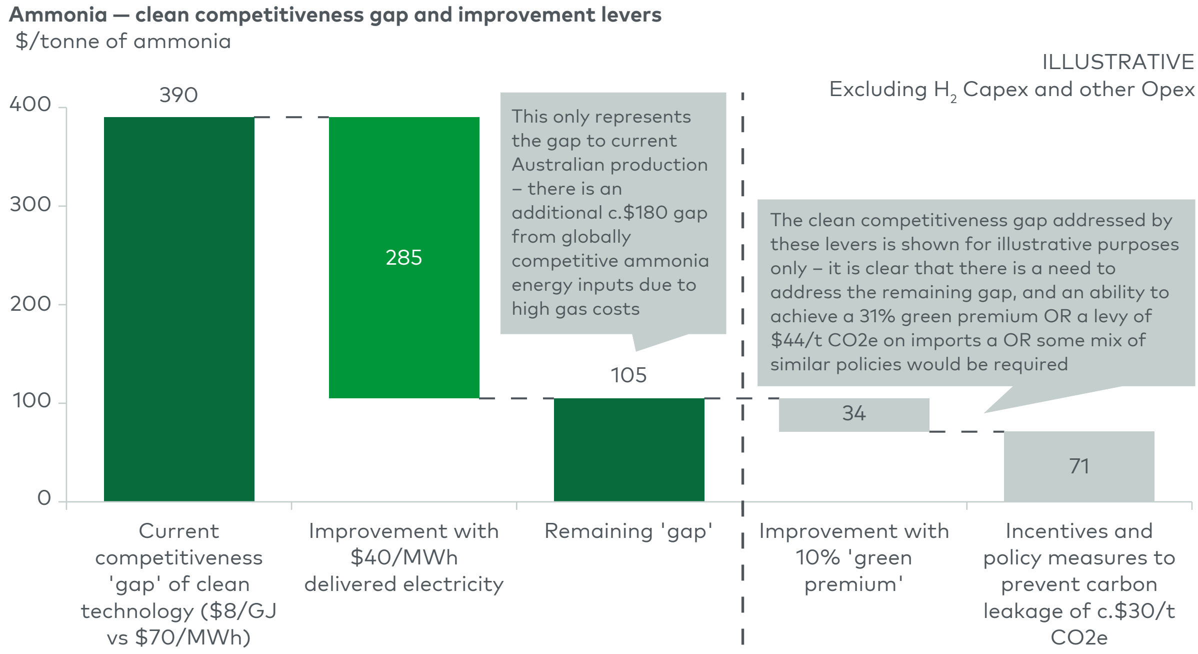
> transition to low emissions production. Without a level playing field through the transition, Australia will lose the opportunities and benefits that a vibrant manufacturing sector provides and will fail to deliver overall global emissions reduction due to 'leakage' to other economies

There are many different mixes of policies to enable Australia's opportunities from low emissions manufacturing, but the evidence base shows that a coherent policy will require all three elements to at least some degree. Taking ammonia as an example (Figure 8), 75% of today's clean technology 'competitiveness gap' versus current Australian production would be addressed with $40/MWh delivered electricity. However, while this is the place to start in terms of building competitiveness, a residual gap remains, providing a role for a 'green premium' and incentives and other policy measures to prevent carbon leakage.

While this simplified illustrative policy solution could enable a competitive environment for low emissions production versus today's production processes, the policy gap is actually even larger when considering that globally competitive ammonia producers benefit from gas prices of around $3/GJ today. If this is calculated using the $8/GJ costs paid on the Australian East Coast, this translates into an additional $180 per tonne of ammonia 'gap' from globally competitive producers who benefit from US or Middle Eastern gas prices.

**Figure 8**

Ammonia — clean competitiveness gap and improvement levers



This only represents the gap to current Australian production – there is an additional c.$180 gap from globally competitive ammonia energy inputs due to high gas costs

The clean competitiveness gap addressed by these levers is shown for illustrative purposes only – it is clear that there is a need to address the remaining gap, and an ability to achieve a 31% green premium OR a levy of $44/t CO2e on imports a OR some mix of similar policies would be required

| | Current competitiveness 'gap' of clean technology ($8/GJ vs $70/MWh) | Improvement with $40/MWh delivered electricity | Remaining 'gap' | Improvement with 10% 'green premium' | Incentives and policy measures to prevent carbon leakage of c.$30/t CO2e |
|---|---|---|---|---|---|
| Policy imperatives | *Scale breakthrough technologies* | *Reduce the cost of clean energy* | *(Use all policy levers to enable competitiveness of Australian manufacturing)* | *Stimulate green manufacturing demand* | *Level the playing field* |
| % of ammonia price | 115% | 84% | 31% | 10% | 21% |

Capital costs of clean technologies also need to be addressed to enable decarbonisation

Note: Excludes $H_2$ CAPEX and other OPEX and any enabling capital investment for manufacturers
Analysis as of July 2021
Source: L.E.K. Industry Net Zero model

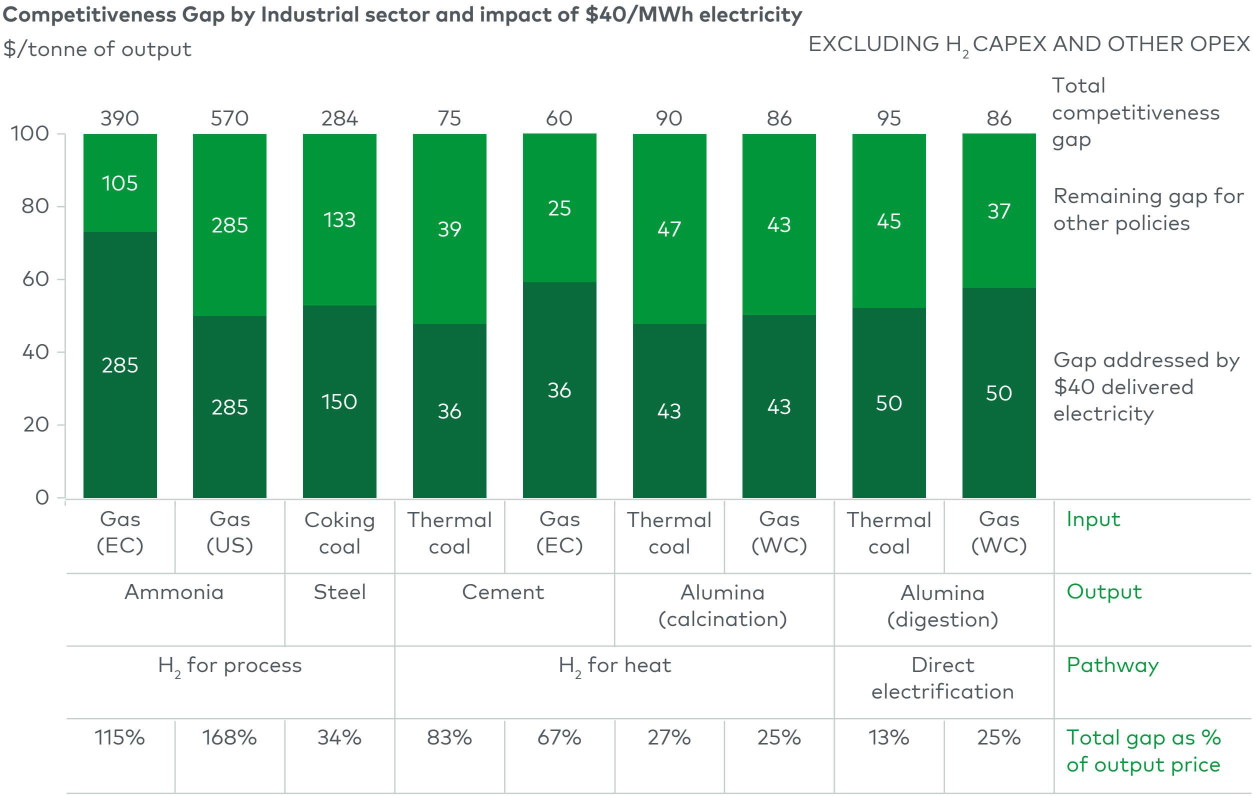
The impact of lower delivered electricity prices in addressing the 'competitiveness gap' is consistent with the economics of the pathways for the other focus industries — $40/MWh delivered electricity would address more than half of the competitiveness gap of clean technologies across all manufacturing verticals but represents a significant challenge to deliver given high firm renewables costs today.

Potential policy levers that can address each element to enable Australia's opportunities from low emissions manufacturing have been outlined in the following table.

While all these potential levers are options for policymakers, the evidence base set out in this perspectives paper demonstrates some clear priorities for inclusion in a coherent policy framework:

**Figure 9**

Clean competitiveness gap by industry sector and impact of $40/MWh electricity



Note: Total competitiveness gap based on $70/MWh delivered electricity and $8/GJ gas today. Excludes $H_2$ CAPEX and other OPEX, and any enabling capital investment for manufacturers Analysis as of July 2021

Source: L.E.K. Industry Net Zero model

**Table 3**

Policy levers for each element enabling Australia's opportunities from low emissions manufacturing

| Element | Issues to be addressed | Potential policy levers |
|---|---|---|
| **Low emissions technology cost competitiveness** | • Technological development<br>• Increased input costs<br>• Infrastructure investment (energy and CCS) | • R&D support<br>• Subsidy<br>• Infrastructure planning<br>• Infrastructure provision |
| **Low emissions product demand and pricing** | • High implicit abatement costs relative to carbon prices<br>• Lack of green premiums | • Standards<br>• Information disclosure<br>• Carbon pricing<br>• Mandates |
| **Australian competitiveness** | • Delivery of emissions reduction<br>• Policy differentials<br>• Trade exposure and emissions leakage | • Emissions intensive, trade exposed (EITE) incentives and policy<br>• Manufacturing industry policy<br>• Long-term emissions policy |

- Commit to **realise the opportunity** of maintaining and growing Australian manufacturing in a low emissions future
- **Recognise the challenges** that will require all three enabling elements of Australia's low emissions manufacturing opportunities to be addressed through manufacturing industry, energy, trade and emissions policies
- Set and deliver more ambitious **low emissions technology targets:**
    - As shown in this paper, the current target of $2/kg hydrogen is not globally competitive for ammonia production.
    - Similarly, wholesale energy prices of c.$70/MWh (before transmission and distribution[4] and $100/MWh electricity storage will not result in globally competitive electricity prices. These risk demand projections and system investment being disconnected from future demand realisation, and a focus on average prices does not address the impacts of increasing spot price volatility in the NEM.
    - Finally, there is a need to accelerate delivery of CCS compression, hub transport (<100km) and storage under $20/t CO2e (noting that many manufacturing sites are located more than 100km from a hub and costs of capture are additional, significant and uncertain).
- Commit to ensuring efficient and effective policy responses are provided that address potentially unintended and unfair cost advantages of **imports with higher embodied carbon**, and avoidance of future 'import dumping' that would harm Australian manufacturers
- Demonstrate leadership from all levels of government and its agencies by **procuring low emissions, Australian-made products** and ensuring that **product and construction standards** encourage innovation and adoption of low emissions products
- Provide globally competitive **incentives**, with support for investment in **R&D** to reduce the costs of low emissions technologies and **promote innovation** that encourages investment throughout Australia's manufacturing value chains

While these policy priorities should be features of a coherent policy framework, they are insufficient on their own, and further measures will be required if Australia is to deliver both emissions reductions and a vibrant Australian manufacturing sector.

## Conclusions

The contribution of Australia's manufacturing sector is significant, as are the carbon emissions from some focus sectors within it. For Australia to maintain and grow the benefits that manufacturing provides and for the world to benefit from emissions reduction, it is important that these verticals can be competitive through Australia's transition to a low emissions economy.

Manufacturing Australia recognises that the playing field on which Australian manufacturers compete is unlikely to be perfectly level — however, for Australian manufacturers to win and the planet to benefit, we need a coherent set of policies that address each of the elements to enable Australia's opportunities from low emissions manufacturing. That is, policies must:

- Target cost-competitive low emissions technology and provide globally competitive energy inputs
- Support demand and enable cost-reflective pricing for low emissions products
- Ensure that imported products are not unfairly advantaged over Australian products due to lower-cost, higher-carbon inputs

There is a role for both the public and private sectors in addressing the challenges and seizing the opportunities of low emissions manufacturing. Many Australian manufacturers have made both medium- and long-term commitments to reduce emissions in their operations. They need a policy environment that recognises the challenges and opportunities of doing this so that they can confidently invest in the future of Australian manufacturing.

# Contribution of Australian manufacturing

### Contribution of Australian manufacturing

**Contribution of Australian manufacturing to the economy and society**

- Australia's manufacturing sector and its capabilities are diverse
- Manufacturing adds value adding to the Australian economy
- It accounts for a large proportion of Australia's international trade
- It provides a large number of skilled, high paying, full time jobs
- Manufacturing has a large footprint in outer-suburban and regional Australia
- Australian manufacturers invest in innovation, automation, and R&D
- It enables valuable skills and investments throughout value chain
- Manufacturing is an important sovereign capability
- It is an ecosystem that supports extensive linkages with other sectors
- Manufacturing supports a resilient energy system
- It closes the loop for the circular economy and benefits the environment
- Manufacturing enables high standards of environmental and consumer protection

## Australia's manufacturing sector and its capabilities are diverse

Australia's manufacturing industry is highly diverse. Its outputs span the fundamental building blocks of modern society — metals, building materials, chemicals, food products and machinery — through to highly specialised and advanced products including solar cells, biomedical sensors and precision cutting tools.

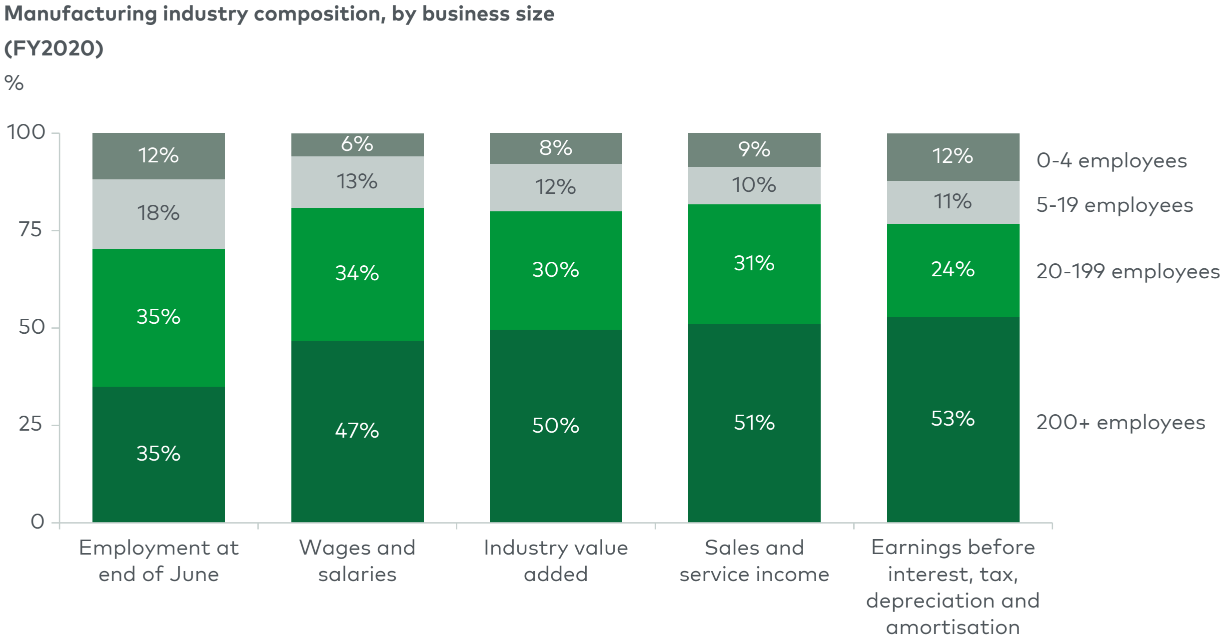
Australian manufacturers are similarly diverse, from small, owner-operated businesses to very large private or publicly listed manufacturing companies, including many of Manufacturing Australia's members. Australia's smaller manufacturing businesses are often highly specialised or important suppliers to the broader sector. Larger manufacturing businesses, although few in number, account for more than a third of jobs.

## Manufacturing adds value to the Australian economy

The Australian manufacturing industry contributed c.5.6% of GDP in FY2019/2020, representing over $108 billion of annual gross value added to the Australian economy.[5] The sector has traditionally played a key role in the Australian economy and was the largest contributor to GDP until the mid-2000s, when it was overtaken by the booming mining industry. Since then, the contribution of Australian manufacturing to real GDP has been growing; however, faster growth in other sectors of the economy means manufacturing now accounts for a smaller proportion of Australian GDP today (c.11%

**Figure 10**

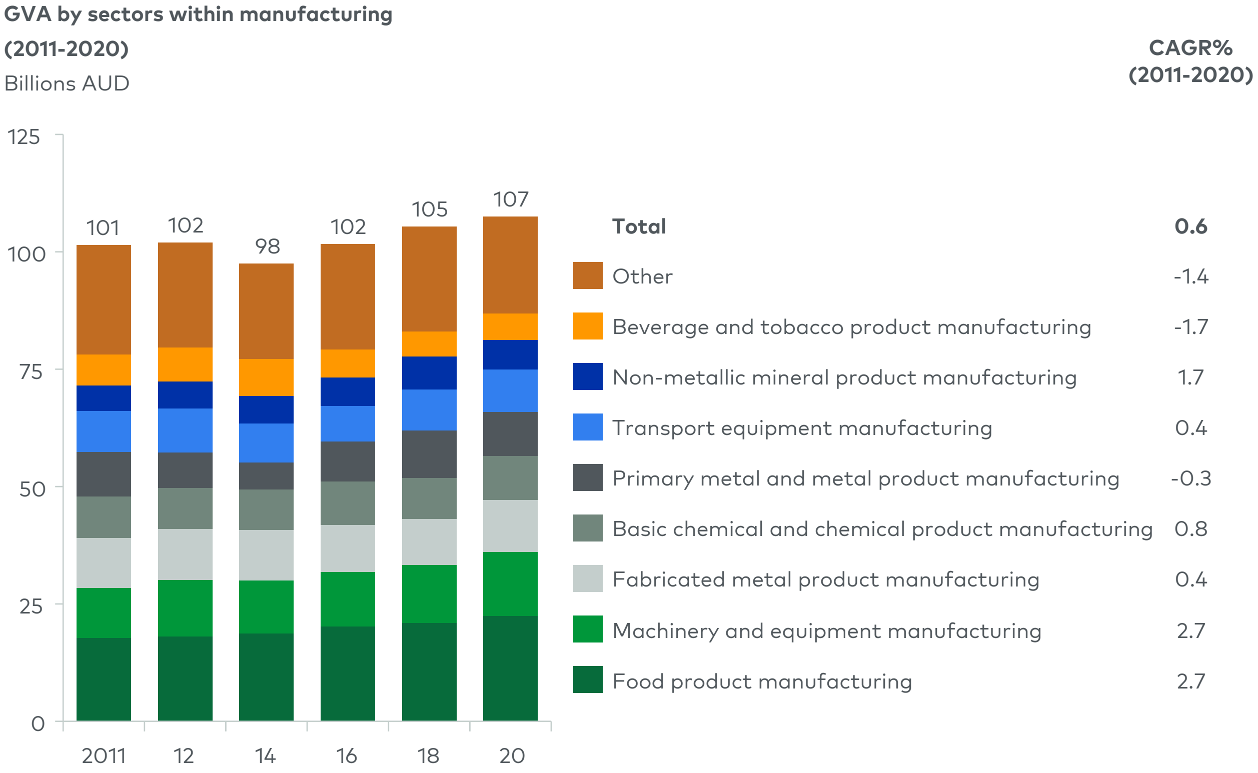
Manufacturing industry composition, by business size (FY2020)



Source: Australian Bureau of Statistics, 81550DO001: Australian Industry 2019-2020

**Figure 11**

Gross value added by industries within the Australian manufacturing sector (2011-2020)



Source: Australian Bureau of Statistics, 81550DO003: Australian Industry 2019-2020 in 1990 vs c.6% in 2020). Over this time frame, manufacturing and mining have effectively swapped positions as the largest contributor to Australian GDP (mining accounted for c.7% in 1990 vs 10% in 2020), as shown in Figure 12.

In addition to the strong contribution to GDP, Australian manufacturing makes other important economy-wide contributions by:

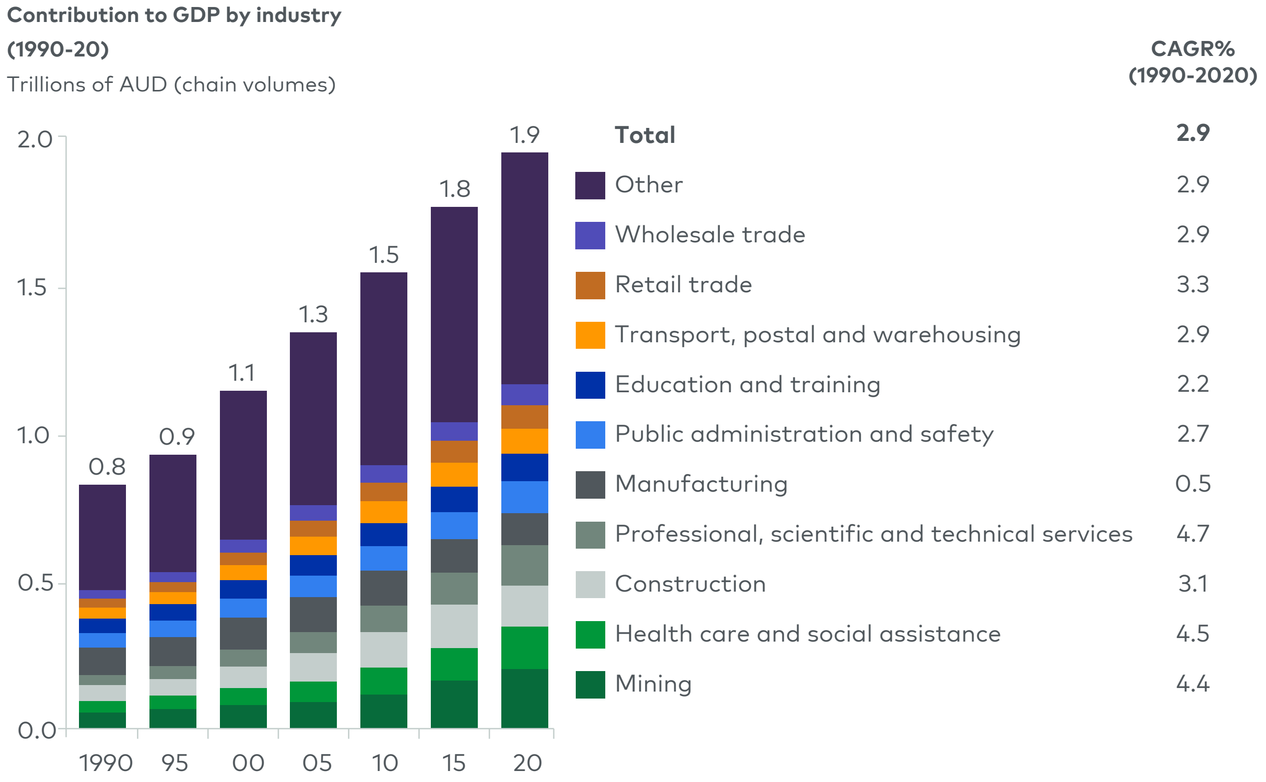
- Accounting for 5% of the capital stock [6] (see Figure 13 )
- Paying 6% of Australian corporate tax[7]
- Contributing $108 billion (or 6.1%) to the Australian economy (real gross value added in 2020, chain volume measure)
- Employing 7% of the Australian workforce (explored further below)

### Manufacturing accounts for a large proportion of Australia's international trade

The manufacturing sector accounted for $83.8 billion (or c.22%) of Australia's merchandise exports in FY2019, second only to mining, where this includes a wide range of commodities including iron ore, thermal and coking coal, oil, and gas (see Figure 14 below).

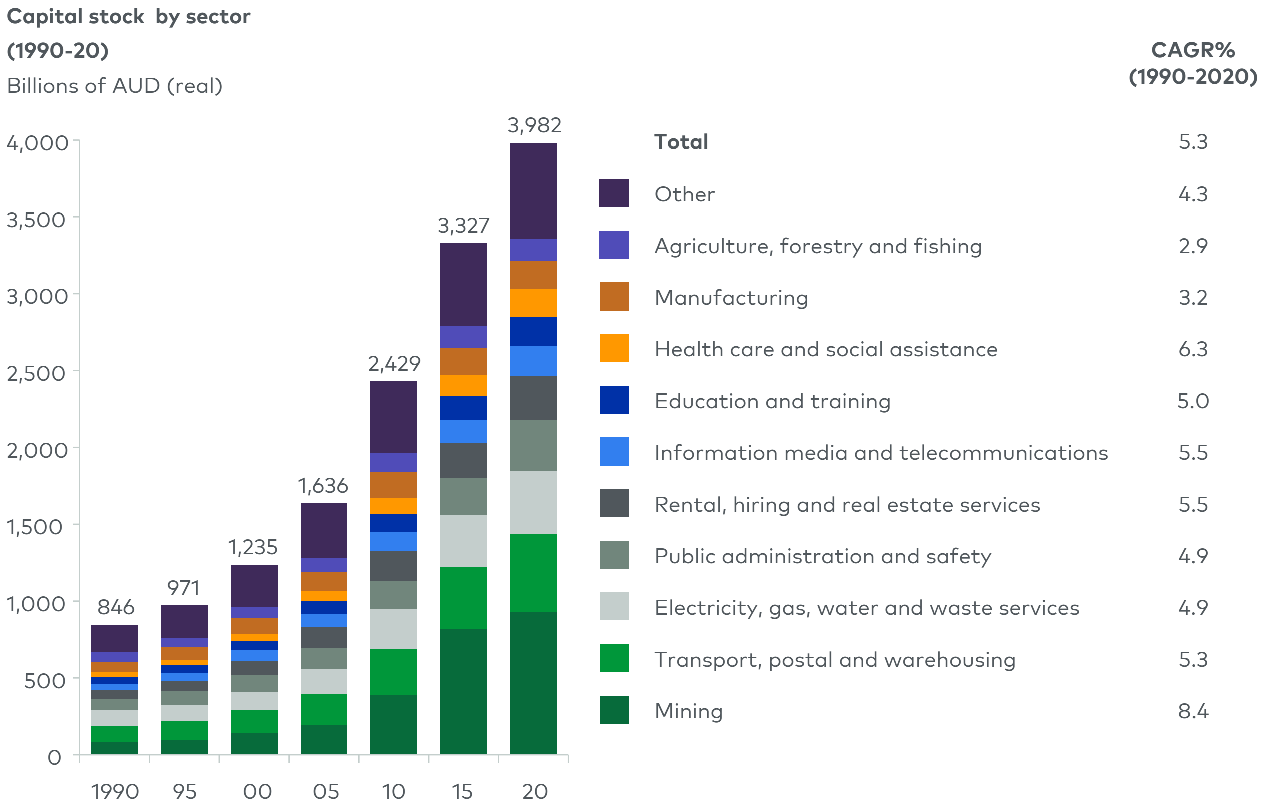
Australia's manufacturing industry also attracted c.$130 billion (12%) of foreign direct investment in Australia in FY2019/2020.

**Figure 12**
Contribution to GDP by sector (1990-2020)



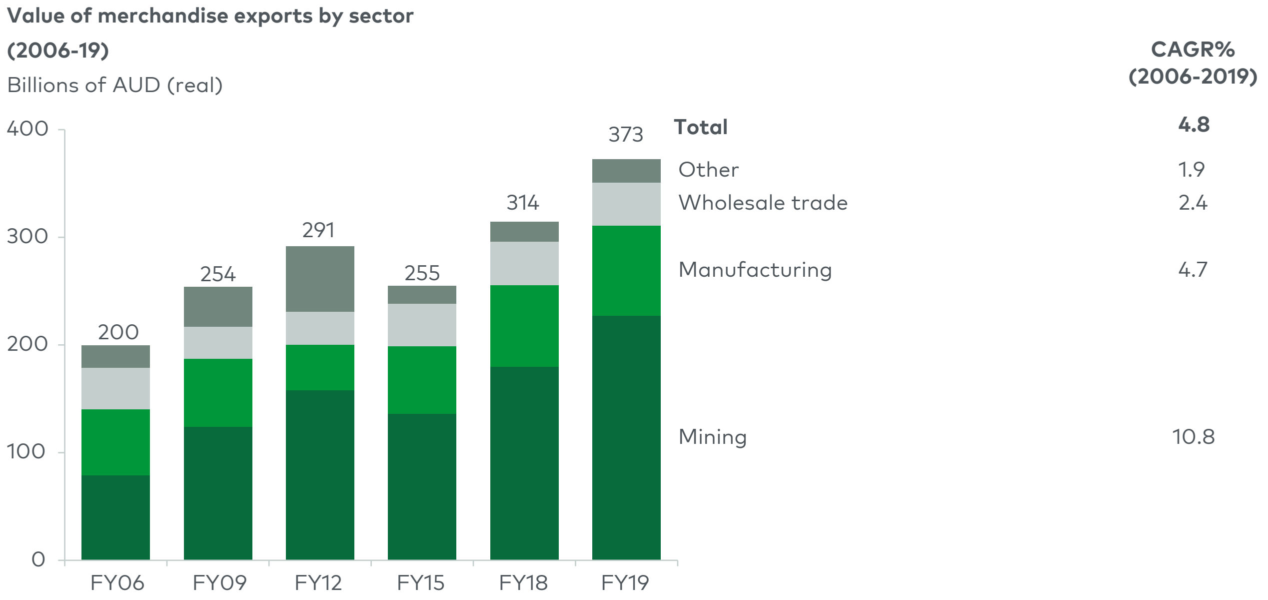
Source: Australian Bureau of Statistics, 5206.0: Australian National Accounts: National Income, Expenditure and Product

**Figure 13**
Capital stock by sector (1990-2020)



Source: Australian Bureau of Statistics, 5204.0: Australian System of National Accounts, Capital Stock, by Industry

**Figure 14**
Value of exported merchandise by sector (FY2006-2019)



Note: Mining exports include oil, gas and coal exports. Manufacturing includes exports of primary metals (aluminium, steel and iron)
Source: Australian Bureau of Statistics, 5368055006: Characteristics of Australian Exporters

The strong growth in the value of manufacturing imports shows a potential opportunity to increase manufacturing to service demand that evidently exists in the Australian market, as seen in Figures 15 and 16.

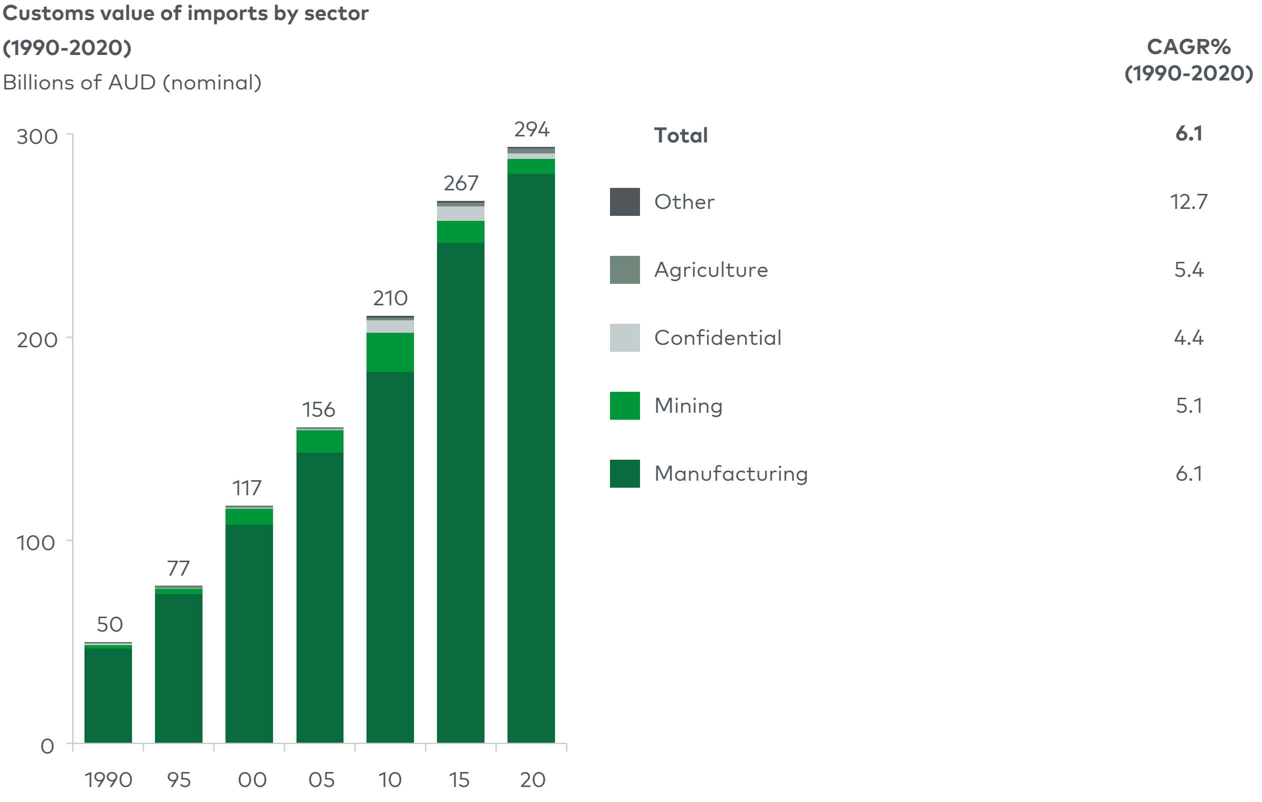
### Australian manufacturing provides a large number of skilled, high-paying, full-time jobs

The Australian manufacturing industry is an important employer, with an estimated c.890,000 workers as of February 2021, which has been broadly steady since 2015.[8] Manufacturing supports 1.3 million jobs, directly and indirectly, accounting for more than 10% of Australia's workforce.[9]

Australian manufacturing jobs are also of high quality:

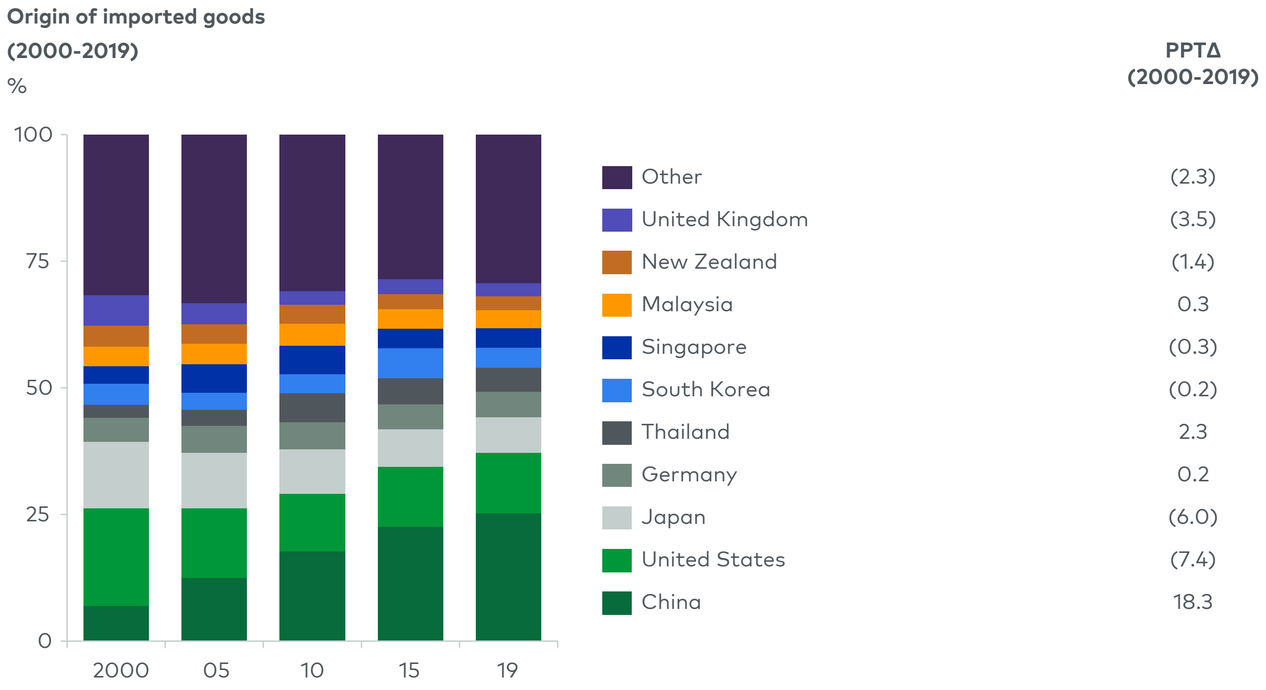
- Mean incomes in the manufacturing sector are $72,100, 28% higher than the national mean income of $56,100[10]
- Approximately 84% of manufacturing industry workers are employed on a full-time basis, which is significantly higher than the national average of c.69%
- Manufacturing workers are often highly skilled and semi-skilled operators, with a combination of vocational, tertiary and on-the-job training with skills over and above service-level jobs

**Figure 15**
Customs value of imports by sector (1990-2020)



Source: ABS - 5368.0 International Trade in Goods and Services, Australia; OECD – Australia, Annual imports historical data

**Figure 16**
Country of origin of imported goods (2000-2019)



Source: ABS - 5368.0 International Trade in Goods and Services, Australia; OECD – Australia, Annual imports historical data

## Manufacturing has a large footprint in outer-suburban and regional Australia

The manufacturing sector is often a linchpin employer in regional areas, with many regional hubs in places like Port Kembla, Gladstone and Devonport and their surrounds benefitting from the strength of manufacturing activities to underpin employment, supporting businesses and infrastructure. Around 25%[11] of manufacturing employment is located in areas outside capital cities, providing strong wages and economic opportunities to these communities.

Manufacturers make significant contributions to their regional communities — two examples from the Manufacturing Australia membership are:

- BlueScope's steelworks at Port Kembla — in New South Wales' (NSW) Illawarra region — is the largest steel production facility in Australia, supporting 3,000 jobs directly and 10,000 contractors, suppliers and other service providers within the Illawarra region[12]
- Tomago directly and indirectly engages over 1,800 people in NSW Hunter region, including a significant number of local contractors, and contributes in excess of $800 million in gross regional product[13]

## Australian manufacturers invest in innovation, automation and R&D

Successful Australian manufacturers are adopting and incorporating advanced technology and automation within their production processes.

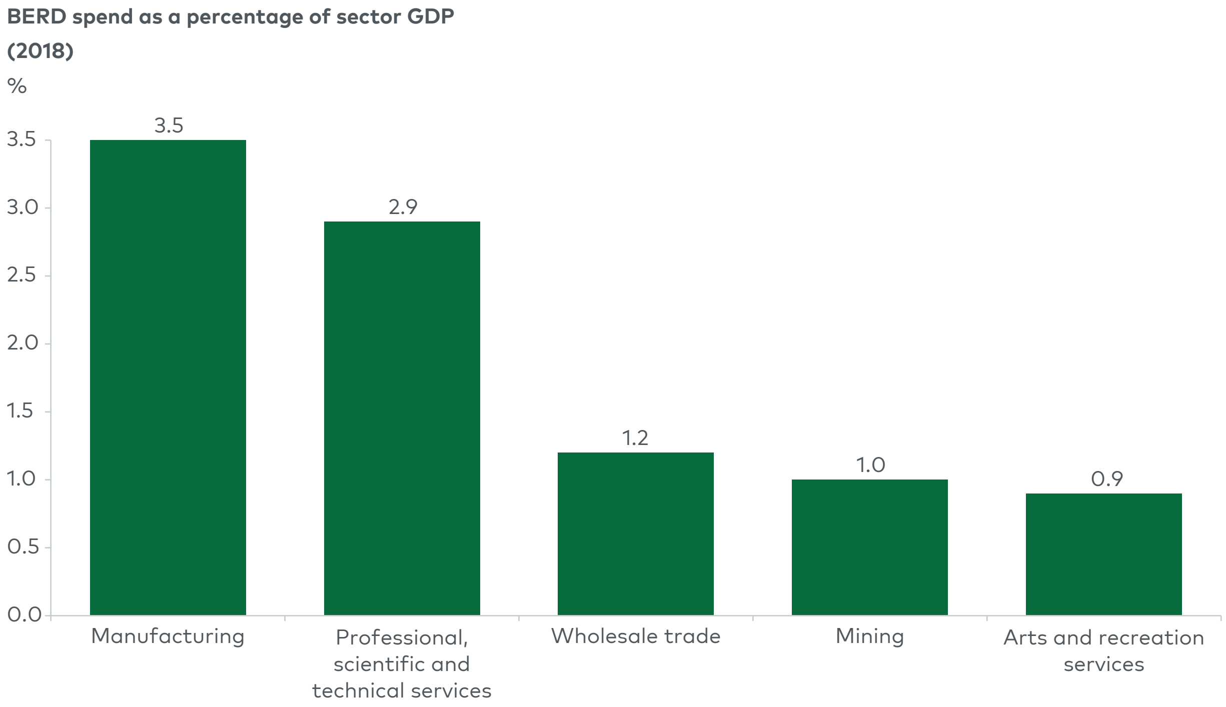
The sector's focus on innovation, automation and R&D is seen through:

- Australian manufacturers spending the greatest proportion of GDP contribution on R&D out of any sector in 2018 (see Figure 17 for top 5 sectors by percentage spend)
- Australian manufacturing businesses spending approximately $4.5 billion on R&D in FY2018, representing c.27% of Australia's total R&D spend, and employing c.19,000 full time equivalent staff engaged in research (representing c.26% of these employees in Australia)[14]
- Manufacturing Australia's members being awarded 643 patents since 2010 (more than 2% of all patents awarded in Australia during the period)[15]

Australian manufacturers have a strong focus on applying technologies in our local context to achieve high levels of efficiency and productivity, alongside benefits of greater customisation and 'servitisation' of manufacturing. These applications are often early in the life cycle and used by global equipment suppliers to showcase their capabilities for deployments in larger markets.

The below case studies demonstrate Australian manufacturers incorporating advanced production technologies when investing in new plants and plant upgrades (see breakout box for case studies).

**Figure 17**
BERD spend as a percentage of sector GDP (2018)



Source: Australian Bureau of Statistics, 81040DO002: Research and Experimental Development, Businesses, Australia, 2017-2018

## Case studies of advanced Australian manufacturing technologies

### DuluxGroup Merrifield

DuluxGroup completed its new Merrifield plant in 2017, investing approximately $165 million and working in partnership with a number of local and global suppliers including Siemens, Dromont, CET, Keisel, Foodmach and Vaughan to apply global best-in-class paint manufacturing capabilities in Victoria.

Paint manufacturing is traditionally a labour-intensive process, due to its being batch-made, requiring 150+ raw materials to produce 800+ SKUs. The new plant embraces automation, with the number of manual raw material additions reducing from 75,000 p.a. at the previous factory to zero at Merrifield.

Using global 'best of breed' technology, combined with novel factory design, DuluxGroup has fully automated while retaining its broad raw material and product formulation range, and also increasing batch size flexibility (with a range from 500 to 30,000 litres), which is a global first for the paint industry.

Using advanced technology, and Industry 4.0 design principles, the factory is very agile, with production time per batch reducing by up to 87.5% and twice as many batches being made per volume alongside the increased batch size flexibility. The complete supply chain information flow and control system is digital. This technology and design approach has also allowed 'new ways of working' where all operators are being multi-skill trained to do all operations jobs on the site.

DuluxGroup's Merrifield factory and Industry 4.0 credentials were showcased by Siemens at the 2018 Hannover Fair — the biggest stand at Hannover, and the first time Siemens had showcased an Australian project.

### Orora investment in best-in-class technology

Orora has invested $200 million in its beverage manufacturing Gawler facility in the past five years, including the G2 furnace rebuild, capacity expansions, mould insourcing, system upgrades and an on-site, automated warehouse capacity.

Orora completed the $35 million warehouse in December 2020 to reduce on-site inventory requirements and reduce off-site pallet storage and transport costs.

Orora has also invested in laser-guided vehicles, providing benefits of delivering optimal storage capacity, greater efficiency and accuracy, and enhanced safety.

(Continued)

Furthermore, a stand-alone embossing and printing machine was purchased and installed by Orora at the Closures Dudley Park site in South Australia. This addition improves production speed by three times over the prior model. Furthermore, the machine is equipped with a high-resolution camera that can automatically detect and reject closures that do not meet Orora's high quality standards.

### CSR's Hebel plant

Hebel is a strong, versatile, high-performance building product made from Autoclaved Aerated Concrete (AAC). CSR Hebel officially launched its new AAC manufacturing facility at Somersby, NSW, on Friday, 11 October 2019. This $75 million investment took over four years to build, doubling current capacity and providing new capability to service the growing demand of the Australian housing market for innovative, quality building products such as Hebel.

The focus of Hebel's new plant included supporting the local economy and minimising the company's carbon footprint. This has underpinned the decision to work with local suppliers, manufacturers and products sourced in the region where possible. As a result, much of the $75 million spend has been spent locally in Australia, and once the plant is running at full capacity, 45 new jobs will have been created for the local community on the NSW Central Coast.

- Of all material produced through Hebel's manufacturing process, 98.5% is recycled by a third-party waste management company with plans to recycle in the plant.
- On-site water catchment captures rainwater which is reused in Hebel's manufacturing process to produce steam for autoclaving.
- Condensate produced during the autoclave process is now captured, and a proportion of this is reused in the manufacturing process. Additionally, condensate heat is reused to reduce gas consumption in the generation of steam, and sophisticated control also allows steam to be shared across autoclaves.

Available in blocks and panels, Hebel is easy to handle, quick to build with and better to live in. Hebel panels contain anti-corrosion steel reinforcement for added strength and are available in a range of lengths for applications including walls, floors and external cladding.

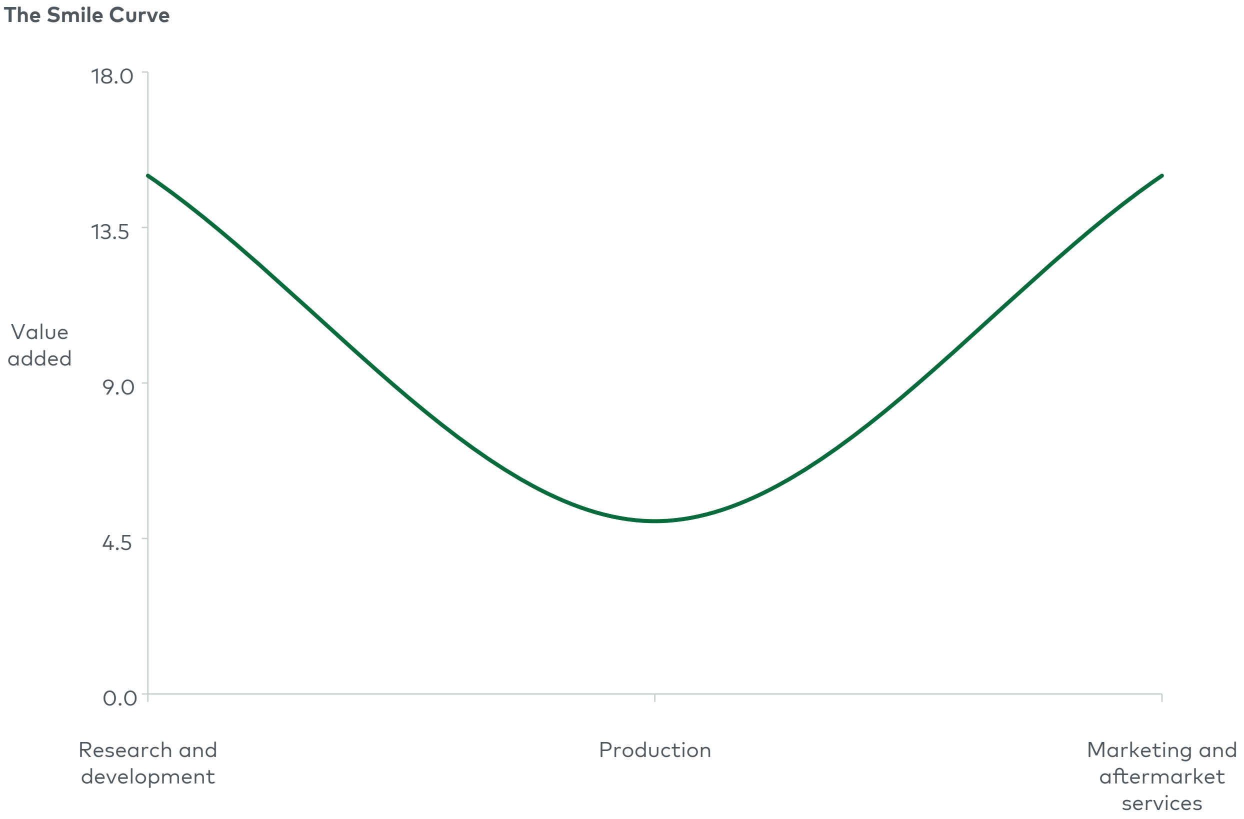
CSR began production of Hebel in Australia over 30 years ago, and still remains the only local manufacturer of AAC in Australia and New Zealand. This is testament to the fact that Hebel continues to deliver innovative, high-quality products and systems that have gained rapid adoption for their fast install times without compromising on quality, and energy-efficient buildings that are design-led and achieve on-trend looks.

### Manufacturing enables skills and investments throughout the value chain

A strong manufacturing sector provides the enabling foundation for further value-add from investing in and developing important skills throughout the value chain, from R&D to marketing and digital. Research has shown that investments in R&D activities and marketing alone can result in lower value creation across the entire value chain, often referred to as the 'smile curve' shown in Figure 18. This concept partly explains why many developed economies have experienced offshoring of low-value and basic manufacturing activities to economies with low labour costs.[16]

Companies maximise value and can earn superior returns where they can develop interdependencies across the value chain — in particular, the ability to identify customer needs, develop innovative solutions, and then deliver products and services that meet customer needs using flexible and responsive manufacturing capabilities. In an economy like Australia with high wages and a high standard of living, this typically means that the integrated manufacturer needs to maintain both a competitive manufacturing cost position and strong R&D and marketing capabilities.

**Figure 18**
The 'smile curve'



Source: Department of Industry, Science, Energy and Resources — Industry Insights, Globalising Australia; Baldwin R, Ito T, and Sato H (2014), Portrait of Factory Asia: Production network in Asia and its implication for growth — the 'smile curve', Institute of Developing Economies Japan External Trade Organization

## Manufacturing is an important sovereign capability

The COVID-19 pandemic has demonstrated the importance of Australia's possessing critical sovereign capabilities in a time of crisis. The existence of a domestic manufacturing sector and associated skill base meant Australia was able to reduce its reliance on international supply chains in the face of disruptions from COVID-19 and provided the flexibility and responsiveness to rapidly create domestic production capacity in the face of critical shortages.

### Case studies of the importance of sovereign Australian manufacturing capabilities: DuluxGroup, Med-Con and ResMed

With assistance from DuluxGroup, Foodmach and the Australian Defence Force (ADF), Med-Con was able to respond to Australia's need for medical masks during the COVID-19 pandemic. Before the pandemic, Med-Con was producing two million masks per year. In response to the COVID-19 pandemic, with support from industry and federal and state governments, Med-Con's mask production increased to manufacture up to 50 million masks every six months.

DuluxGroup assisted Med-Con in scaling up so that it could transition from the ADF temporarily operating the plant (the Australian government deployed 14 ADF personnel to the Med-Con factory to support the on-ground production capability) to taking full control. DuluxGroup also worked with Foodmach, the manufacturer of the needed additional mask machines, to shorten the lead time for manufacturing and installing the additional mask making machines, and directly assisted the identification of needed ancillary machinery suppliers, factory validation and procurement in China on behalf of Med-Con.

At the same time, Australian med-tech manufacturer ResMed's local production of ventilators was sufficiently strong that Australia became a net exporter of ventilators. ResMed provided 5,500 ventilators to the Australian federal government, meeting national manufacturing targets. ResMed was also able to supply the United States Federal Emergency Management Agency (FEMA) with 2,550 units when traditional global supply chains could not service the significant increase in demand.

### Australian Defence Force personnel supporting Med-Con's mask production

Coronavirus fires up production at Australia's only medical mask factory.
Source: ABC.net

There are specific sectors where a domestic manufacturing capability is of strategic importance to maintain:

- **Ammonia** is a critical input into fertilisers for food production, as well as explosives
- **Cement** is a critical material for construction of the infrastructure required for a modern economy
- **Steel** and **aluminium** are also important materials to enable construction and manufacturing of other goods

### Manufacturing is an ecosystem that supports extensive linkages with other sectors

Large-scale manufacturing depends on an ecosystem of supporting businesses and skilled jobs surrounding manufacturing facilities and provides economic benefits in the local communities of the manufacturers. Manufacturing Australia's 12 members have over 25,000 downstream suppliers combined who pay wages to their staff and support further suppliers.

Large manufacturers also support a broader industrial base that provides benefits across other parts of the economy. As an example, steel production creates excess oxygen that can be supplied to hospitals for use in ventilators, which have been critical throughout the COVID-19 pandemic. For example, Port Kembla Steelworks provides oxygen to Coregas, which collects and supplies oxygen to hospitals throughout NSW.

### Manufacturing supports a resilient Australian energy system

Manufacturers are large industrial users of energy, providing stable demand along with flexibility to quickly reduce load to provide stability to national power grids during periods of high demand.

Tomago Aluminium is Australia's largest electricity consumer, accounting for c.10% of NSW's electricity demand. Tomago has the ability to reduce its load in part during peaking demand or in full during an emergency, helping the Australian Energy Market Operator (AEMO) to alleviate pressure and balance supply and demand on the grid, and keep the lights on for the rest of the market.

As the largest interruptible electricity load in the country, this makes Tomago critical to the stability of the national electricity grid.[17] If NSW did not have an operational smelter, it would be significantly more difficult to reduce demand load when system events compromise the electricity grid.

In January 2020, the NSW grid lost c.2,000MW of power when bushfires disrupted transmission from Snowy Hydro. The AEMO requested that Tomago Aluminium pause operations of two potlines, releasing a significant amount of supply back into the grid, helping to avoid state-wide blackouts.[18] Additionally, in January 2019, Tomago Aluminium put 600MW[19] of electricity back into the power grid due to enormous pressure on NSW's electricity supply caused by record summer temperatures, catastrophic bushfires and air conditioning units working overtime.

> **"New South Wales would be hit with large-scale blackouts if the smelter didn't help the market operator control loads over the hot summer months."**
>
> *Matt Howell, CEO of Tomago Aluminium*

While Tomago is proud of the contribution it makes to grid resilience, it is more frequently being asked to reduce its load when prices and demand are high beyond what was intended when the facility was built and energy contracts entered, with almost 11 hours of power interruptions to its potlines in January 2021 alone.[20]

### Australian manufacturing closes the loop for the circular economy

Australian manufacturers play a key role in 'closing the loop' for the circular economy, enabling improved material and by-product recovery and reuse through innovative manufacturing approaches. This combines to achieve benefits both for diversion of waste from landfill and reducing carbon emissions embedded in products. Manufacturing Australia members provide large-scale opportunities for processing by-products in one sector to become valuable inputs in other sectors — for example:

- Cement and concrete producers utilise fly ash, a by-product from coal-fired power generation, and blast furnace slag, a by-product from iron and steelmaking, to increase the strength and durability of concrete and supplement virgin clinker in cement
- Cement producers also utilise alternative fuels derived from recycled tyres, oils and other forms of waste to reduce their reliance on energy from fossil fuels
- Clinker kilns can also destroy hazardous wastes through combustion at high temperatures — for example, per- and polyfluoroalkyl substances (PFAS) do not fully break down naturally and there is a need to decontaminate sites (such as where PFAS was used for airport firefighting purposes) that can be met as a result of the existence of Australian manufacturing
- Ammonia producers capture carbon dioxide, which is utilised by the food and beverage industry and the medical sector
- Urea manufacturers produce the key ingredient for the emissions control additive known as AdBlue, which is essential to the continued operation of Australia's diesel truck and vehicle fleet

Future development of the circular economy will require the vibrant manufacturing sector and investment in R&D to create approaches for recycling/utilisation of waste streams that are not viable or have not been tested today in the Australian context. Partnerships between waste collectors, processors, manufacturers and users to create circular economy loops are becoming more common, but the economy is only starting its journey towards being truly circular.

### Australian manufacturing enables high standards of environmental and consumer protection

Australian manufacturers are committed to serving the Australian market and protecting consumers and the environment. The substantial fixed capital investments that are required for manufacturing demonstrate the commitment of Australian manufacturers to serve the market and signal an assurance of meeting legal requirements and societal expectations in Australia.

The actions of Manufacturing Australia members demonstrate the commitment of manufacturers to consumers and the environment:

- **CSR** has demonstrated to the building industry and consumers how innovative design and application of building materials can deliver an eight-star energy-efficient home that accounts for 85% less emissions than a standard house.
- **DuluxGroup** has reduced the environmental impact of its products by partnering with several large construction companies to collect and recycle their used water-based paint and paint drums, and is a founding member of Paintback, an industry initiative to treat waste painting products, diverting waste paint and packaging from landfill.
- **Rheem** has developed the Solahart PowerStore water heater, which connects to a network of smart products and uses data to assess when excess electricity is generated from rooftop solar panels, redirecting this to heat water. Through aligning product development to Australian data communication protocols and governments providing clear and consistent responses to well-articulated public policy outcomes, innovative products like PowerStore water heaters have the potential to drive down water heating costs, improve grid supply and stability, and deliver environmental outcomes.

In contrast, imported products can in some instances present issues for compliance with Australian standards and consumer protection measures, as demonstrated by the need for schemes like Victoria's Statewide Cladding Audit. This scheme was created to reduce fire safety risks from combustible cladding that was installed in buildings despite not meeting National Construction Code requirements.

Warranties and other consumer rights can also be challenging to enforce in practice for imported products where the manufacturer has limited or no presence in Australia.

### Case study of Brickworks lowering emissions using the circular economy and advanced technology

Brickworks has a successful track record of implementing bioenergy and low carbon fuel projects.

At its Austral Bricks Horsley Park plant, Brickworks has used landfill gas in two kilns since 203/14, substituting up to one third of the kiln's natural gas requirements. The combustion of landfill gas emits 10 times less carbon than natural gas, taking into account emission that would have occurred otherwise. Horsley Park used 223,597 GJ of landfill gas throughout FY20, offsetting approximately 10,442 tonnes of carbon, equivalent to the energy used in 1,200 homes for one year.

Brickworks is also demonstrating efficiencies through leading manufacturing excellence with its Horsley Park Plant 22 Upgrade that will upgrade the site into a state-of-the-art brick manufacturing facility. At the heart of the new Plant 22 operation will be a JC Steele 120 extruder, a world first, exclusively built for Brickworks. The new kiln will push the limits of brick production efficiency to deliver best in its class fuel efficiency and product quality, setting a new standard for brick manufacturing.

Looking to the future, Brickworks is actively developing its long-term lower carbon energy pathway, with focused investment areas including:

- Brickworks Biogas Circular Economy Investigation Study to explore the feasibility of biogas from anaerobic digestion of organic material
- Brickworks Hydrogen Feasibility Study, in partnership with Murdoch University, to explore the potential for hydrogen to be used as kiln fuel in the manufacture of clay bricks
- Review of renewable electricity commercial viability for all new plants

Source: Brickworks Low Emission Technology Statement

## Snapshot of Australian manufacturing and its social and economic contribution

### Manufacturing in Australia Snapshot

Australia's manufacturing sector includes a diverse range of businesses that produce outputs including metals, building materials, chemicals, textiles, food products and machinery

**$108 billion** contributed to the national economy by the manufacturing sector, representing **5.6% of GDP** in FY20

**$83 billion** worth of manufacturing merchandise exported in FY19-22% of all Australian exports – and attracted $130 billion of foreign investment in Australia

**1.1% p.a.** reduction in the emissions intensity of Australian manufacturing since 1990, delivering almost **30% less C02e per dollar** of real GDP contributions over this period

**$4.5 billion on R&D** was spent by the manufacturing industry in FY18, 27% of Australia's total R&D spend. It employs **19,000** full-time equivalent staff engaged in research

**c.2%** of all Australian patents between 2010-21 were awarded to Manufacturing Australia's members

**890,000** jobs are supported by the manufacturing industry, of which **84%** are employed on a full time basis, **69% higher** than the national average

# Steel

Steel is vital to modern economies and is the backbone of the construction, infrastructure and manufacturing industries, with more than 1.8 billion tonnes of steel produced worldwide in 2020.[21] It is the second most abundant man-made bulk material on earth after cement,[22] and the second-largest commodity value chain after crude oil.[23] Global demand for steel is forecast to increase by more than a third by the end of[24] Steel production is highly carbon intensive. For every tonne of steel produced in 2019, 1.83 tonnes of carbon dioxide were emitted,[25] with much of this linked to the use of metallurgical coal both as an input into the steelmaking process and as the source of 75% of steelmaking energy demand. The global iron and steel sector directly accounts for c.2.6 gigatonnes of CO2 emissions annually (including process emissions), which is c.7% of global energy emissions[26] and c.2.1% of Australia's greenhouse gas (GHG) emissions.[27] In order to ensure a sustainable future, the industry must find ways to reduce its GHG emissions in support of international goals to limit further temperature increases.

## 1.1 Steel production today

Steel is an alloy of iron and carbon. It typically contains less than 2% carbon, and is also alloyed with other elements that determine the grade and therefore use of the steel. For example, stainless steels typically contain significant amounts of nickel and chromium.

To produce steel, oxygen must be removed from iron ore through the chemical process of reduction, where oxygen from iron oxides bonds with a reductant containing carbon monoxide or hydrogen at temperatures of c.850°C to 1,500°C.[28] The need for high temperatures and the use of carbon as a reductant result in high CO2 emissions from steel production.

There are currently two major commercial processes used for steel production, and each has substantially different CO2 emissions footprints.

### Integrated steelmaking (BF-BOF)

The integrated steelmaking process using a traditional **blast furnace and basic oxygen furnace (BF-BOF)** accounts for c.73% of steel production globally and c.74% of steel production in Australia.[29] It is also the only major approach globally that produces new, 'virgin' steel.

For this process, iron is typically produced by feeding a blast furnace with sinter (iron ore fines agglomerated into a product of suitable size and strength at high temperatures using metallurgical coal) and coke (metallurgical coal that has been heated to high temperatures in the absence of oxygen to create a physically strong, porous form suitable for its role in the blast furnace). Coke reacts with the oxygen in the 'blast' to produce carbon monoxide, which acts as the reductant to remove oxygen from the iron oxides in the sinter. The energy required for smelting also comes from the combustion of the coke. The resulting liquid iron is fed into a basic oxygen furnace where oxygen is injected at high velocity to react with, and remove, excess carbon, and different alloys are added to produce the required grades of steel. Each of these steps ultimately releases carbon dioxide, either from reactions in the steelmaking process or combustion to provide thermal energy required for the process.

On average, the emissions intensity for steel produced using BF-BOF technology is c.2 tonnes of CO2 per tonne of steel product, of which 1.4t is direct emissions and 0.6t is indirect emissions.[30]

### Electric steelmaking

The electric steelmaking process uses electric arc furnace (EAF) technology to produce steel, where steel scrap is the major iron feedstock material. EAFs use high currents of electricity to melt the scrap to produce steel. EAF technology accounts for c.26% of steel production globally and c.26% of steel production in Australia.[31] Scrap-based EAF has a carbon emissions intensity of 0.4t CO2/t.[32]

The quality of the steel produced via the EAF route is dependent on the source and quality of the input materials.[33] Because of this, it is often necessary to add a high-quality iron source to achieve the desired steel quality. The amount of steel production via scrap-based EAF is also limited by the availability of cost-effective, high-quality scrap steel.

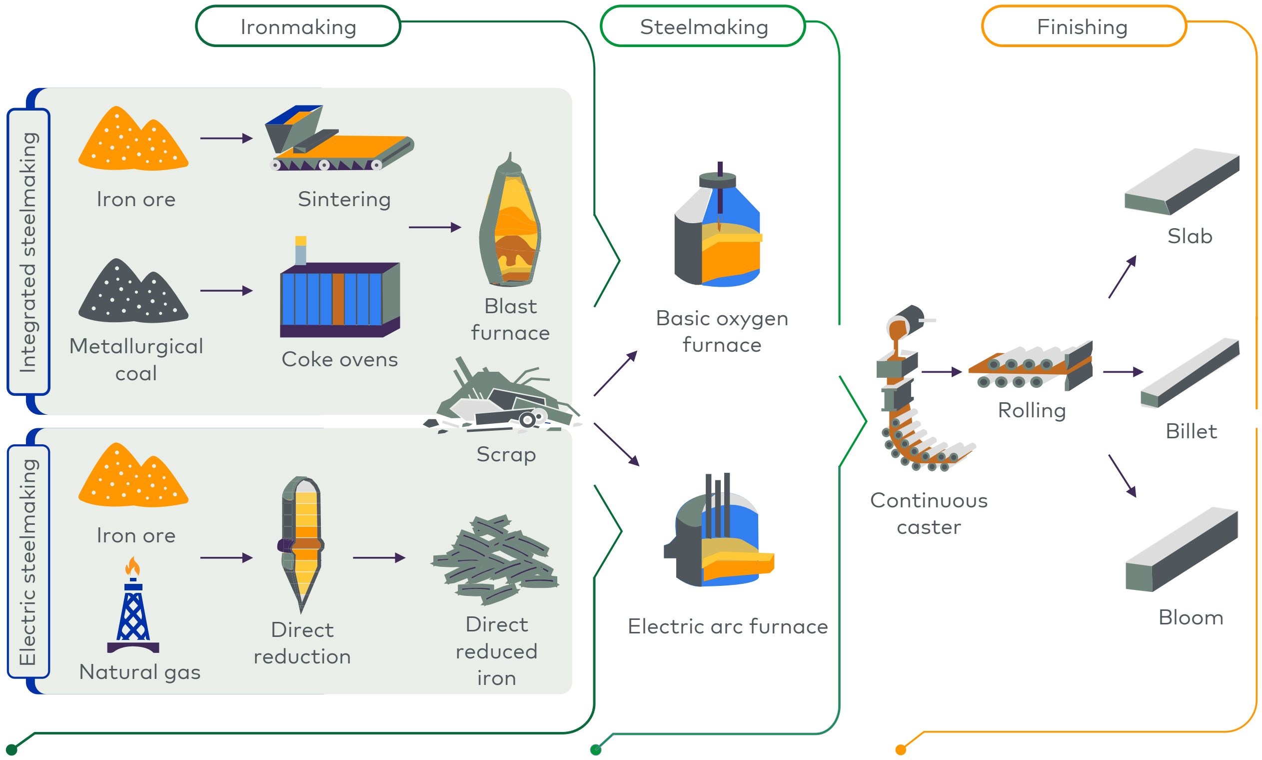
A more recent addition to EAF steelmaking is its combination with a direct reduced iron (DRI) plant, with the most common form of DRI produced via a natural gas-fired shaft furnace. DRI is made by removing oxygen from iron ore (generally in the form of lump or pellets) to produce metallic iron in the solid state, and currently relies on natural gas being reformed into carbon monoxide and hydrogen as the reductant. One hundred million tonnes of iron are now produced via DRI plants per year.[34]

Natural gas-based DRI-EAF results in 1.4t CO2/t in emissions.[35] As an example of underlying emissions from natural gas-based DRI-EAF, 1.0t CO2/t is the result of direct emissions, and 0.4t CO2/t is indirect emissions from electricity generation.[36]

## 1.2 Australian context for steel

Australia accounts for less than 1% of global crude steel production and is a net importer of steel[37] — in 2019, Australia produced c.5.5Mt of crude steel, and domestic crude steel consumption was c.6.1Mt.[38] Australian steel producers therefore compete against imported steel, including from China, where c.56% of global crude steel production occurred in 2020. Other major import competitors include South Korea, Taiwan, India and Japan.[39] Although Australia is a net importer of steel, BlueScope exports up to approximately 800,000 tonnes of steel products per annum from Australia, with principal export markets including North America and South East Asia.[40]

**Figure 19**
Iron and steelmaking processes



Source: 'BHP, Pathways to Decarbonisation', 5 November 2020 (diagram adapted)

While Australia's steel industry is small relative to other countries, it is a significant employer and contributor to the economy. The Australian steel supply chain, from iron and steel production through to downstream fabrication, employed 113,000 people in 2019-2020[41] and generated annual revenue of c.$29 billion.[42]

The Australian steel industry consists of two main steel producers, including: **BlueScope Steel** (flat steel products), **GFG Alliance's Liberty Primary Steel** (hot rolled structural and rail long steel products), and GFG Alliance's **InfraBuild** (reinforcing products, merchant bar, and pipe and tube).

Amongst these producers, crude steel is only produced by BlueScope and GFG Alliance, both of whom have significant existing capital assets deployed:

- **BlueScope Steel** operates an integrated blast furnace and steel mill located at Port Kembla, New South Wales (NSW), that has an annual production capacity of approximately 3.1Mt of crude steel. Steel coating and painting plants are located at Springhill (adjacent to Port Kembla Steelworks), Erskine Park, New South Wales (NSW); Hastings, Victoria (VIC); and Acacia Ridge, Queensland (QLD). BlueScope also operates pipe and tube manufacturing facilities in Adelaide and Brisbane, and national networks of distribution and rollforming facilities.[43]

- **GFG Alliance's Liberty Primary Steel** operates an integrated blast furnace and steel mill located at Whyalla, South Australia (SA), that has an annual production capacity of c.1.25Mt of cast steel and hot rolled products.[44] **InfraBuild,** its construction steel maker, operates electric arc furnaces in Sydney, NSW, and Laverton, VIC, with an annual steel production capacity of c.1.5Mt, as well as four rod and bar rolling mills.[45]

## 1.3 Challenges in transitioning to net zero emissions

There are several challenges to achieving the goal of net zero emissions in the Australian steel industry that are not simply addressed by adopting general zero-emissions technologies used in other sectors like electrified transport or renewable electricity for current electricity requirements.

### a. Technology readiness and choices

There is significant research and development being undertaken globally to identify and implement technologies to reduce/eliminate the emissions from the manufacturing of steel. The potential approaches to emissions reduction vary in their technology maturity (readiness), complexity, cost and level of CO2 reduction. The following table provides examples of the potential emissions reduction approaches, categorised under five main headings.

**Efficiency and alternative feedstock options** only reduce CO2 emissions rather than eliminate emissions completely. These options could be effective interim steps that can be implemented in the short term but are unlikely to be a long-term solution.

**Increased recycling** using the EAF process, commonly used today to recycle scrap, can utilise renewable energy to produce steel with very low or almost zero emissions. However, scrap metal is in finite supply and the expectation is that there is insufficient supply of scrap to meet total global steel demand. The International Energy Agency (IEA) forecasts that by 2050 only c.36% of global steel will be produced via scrap-based electric furnaces under the Stated Policy Scenario, given scrap availability and total steel demand.

**Carbon capture, use and storage** (CCUS) is another potential option for decarbonisation; however, there are several challenges for its application in the steel industry:

- Integrated steelmaking has multiple sources of CO2 across the plant (e.g. sintering and coke production, blast furnace, basic oxygen furnace) with varying concentrations, making capture diffuse, difficult and expensive
- Carbon capture and storage (CCS) is best implemented where there is a storage basin for the CO2 available in close proximity to steelmaking facilities; gas transport (e.g. by pipeline or ship) adds to the cost of the solution

**Table 4**
Potential emissions reduction for steel

| **Emissions reduction options** | **Increased efficiency** | **Alternative feedstock** | **Increased recycling** | **Carbon capture, use and storage (CCUS)** | **Breakthrough production technologies** |
|---|---|---|---|---|---|
| **Description** | Improve efficiency of existing BF-BOF operations | Use alternate feedstocks to act as a reductant | Avoid emissions from new virgin steel production by using more recycled scrap in EAFs | Capture emissions from existing operations and either use or store CO2 | Replace BF-BOF with commercial application of breakthrough steel production technologies |
| **Examples** | • Waste heat recovery<br>• Increase scrap-to-steel ratio<br>• Increase use of higher-quality iron ore and/or premium hard coking coal | • Using biomass as a reductant in a blast furnace<br>• Using hydrogen as some of the reductant in a blast furnace<br>*e.g. Charcoal is commercially used to substitute for a proportion of coal used in blast furnaces, primarily in Brazil* | • EAF plants are currently being used globally to melt scrap — accounts for c.50% of steel production outside of China<br>• EAF based on renewable energy has the potential for significant emissions reduction | • Capturing and using CO2 for industrial uses like food and beverage manufacturing or producing biofuels or chemicals<br>• Capturing and storing CO2 from across some or all of an integrated steel plant<br>*e.g. COURSE50 in Japan targets 30% CO2 emissions reduction from BF-BOF by capturing CO2 from the BF gases and using a higher $H_2$ content to partially substitute for coke, with demonstration scheduled for 2030 and commercial implementation by 2050* | DRI-EAF process using:<br>• Natural gas and CCUS<br>• Hydrogen<br>• Direct electrification<br>*e.g. The HYBRIT project began operating a pilot plant in August 2020 in Sweden, targeting a 1Mt/year demonstration plant by 2025 at 0.025t CO2/t, assuming zero emissions electricity powering the EAF and green hydrogen feeding the DRI. The HYBRIT plant is currently producing sponge iron at pilot scale, but this technology is yet to be commercialised.* |
| **Timing (years)** | Now | 0-5 | 0-5 | 5-10 | 10+ |
| **Status** | Technology readily available | Requires a secure supply chain for biomass | Technology readily available, volume limited by scrap availability and capital investment in renewable energy. Contaminants in scrap may limit use for some steel grades. Pig iron addition may be required to produce some end products. | Not available on industrial scale, is high cost and difficult to retrofit to existing BF-BOF operations | Natural gas-based DRI-EAF is available today; however, CCUS is not at industrial scale.<br>Hydrogen-based DRI-EAF technology currently not proven or available at industrial scale and is high cost. |

Decreasing level of CO2 emissions →

For these reasons, the application of CCUS within steelmaking is more complex than in some other emissions-intensive industries, and therefore less likely to become the preferred decarbonisation technology pathway for Australian producers.

**Hydrogen-based DRI-EAF** ($H_2$ natural gas for thermal energy and as a reductant in BF-BOF steelmaking and natural gas-based DRI, respectively. Minor emissions arise from the use of certain process equipment, and a small amount of coal which must be used in the manufacturing process.[46] However, the technology is currently only at the pilot stage of development.

Given the early stage of technology development and deployment, the IEA estimates that only c.8% of worldwide production capacity by 2050 (Sustainable Development Scenario) will be produced utilising $H_2$ DRI-EAF technology. BF-BOF iron and steelmaking will still comprise between c.30% (Stated Policies Scenario) and c.52% (Sustainable Development Scenario) of worldwide production capacity by 2050.[47] Therefore, finding ways to make BF-BOF iron and steelmaking significantly less emissions intensive will be almost as important as developing breakthrough technologies.

### b. Delivery of cost-competitive energy

Globally cost-competitive low/no emissions energy will be a key factor in driving the decarbonisation of the steel industry.

Alternatives to the current BF-BOF process (e.g. DRI) will significantly increase demand for energy in the form of either hydrogen and/or natural gas (in combination with CCUS), which replaces coal to reduce the iron ore. Production of steel using EAFs will also require zero emissions electricity to power the EAF.

For example, the $H_2$ DRI-EAF process requires hydrogen to be produced via electrolysis using renewable electricity or via steam methane reforming of natural gas in combination with CCUS. The energy required to produce 3.1Mt of steel would be 12.1TWh. This is approximately 22% of the total renewable electricity generated in Australia in 2019.[48]

### c. Development of alternative reductant supply chains

The size and cost of these supply chains are significant. For example, to produce 4.35Mt of 'green' steel, equivalent to BlueScope's Port Kembla and GFG Alliance's Whyalla annual production, c.310kt of hydrogen would be required. This in turn would require c.1,600MW of electrolysis-based hydrogen production, which is equivalent to approximately eight of the world's largest currently planned electrolysis plants (e.g. in May 2020, Shell announced plans for a 200MW electrolyser in Rotterdam by 2023).[49]

The cost of hydrogen will also need to decrease dramatically to incentivise the adoption of 'green' steel technology. The current price of hydrogen from electrolysis in Australia is estimated at between $6.50/kg and $7.50/kg, but this is forecast to fall to $2.00/kg to $3.50/kg by 2030. To achieve cost parity (on an operating cost-only basis) with hard coking coal at $175/tonne, hydrogen would need to be priced at $0.65/kg.

Establishing the required capacity and infrastructure at the scale necessary to enable hydrogen-based steel production would significantly influence the feasibility and timing for 'green' steel manufacturing in Australia.

### d. Availability of suitable and competitive raw inputs

A key challenge in adopting DRI technology is domestically sourcing cost-effective iron ores of the right grade to produce the required pellets for DRI. The DRI steelmaking process currently requires the use of iron ore pellets with 67% to 68% iron (Fe) content. Pellets are often made from magnetite ore, or friable hematite, and the ores are typically beneficiated to generate a product with low impurities (e.g. below 3% in contaminant materials such as silica and alumina). Today, only an estimated 24% of global iron ore production is pelletised, with the remainder being directly shipped lump and fines currently unsuitable for DRI processes. Pelletisation and ores with higher iron ore content increase the cost of raw inputs versus the BF-BOF process today.

A project has recently been announced (Primetals Technologies' hydrogen-based fine-ore reduction (HYFOR) pilot project) to trial DRI technology that can directly use fine iron ore concentrates from beneficiated ore (without the need for a pelletising process). However, this will still need to be proven at scale and could impact the timing of 'green' steel technology adoption.

### e. Rate of global steel industry decarbonisation

The rate at which the steel industry decarbonises globally will vary greatly by region. There is unlikely to be a single low or zero emissions iron and steelmaking technology adopted worldwide. BHP considers that regional decarbonisation pathways will not easily converge due to differences in the age of existing infrastructure, availability of low carbon fuels, domestic carbon policies and net steel trading positions.

The decarbonisation transition period may disrupt any views of a level playing field across global regions. Given the Australian steel industry is trade exposed with markets often distorted by subsidies, trade barriers and overcapacity, the adoption of emissions-reduction technologies during this transitionary period will be influenced in practice by the level of incentives/disincentives relative to other regions.

### f. Capital intensity

The steel industry is highly capital intensive, with assets that have long (often multi-decade) lifetimes. The replacement value of existing assets (i.e. BF-BOF) globally is estimated in the range of US$1.5 trillion to US$2.0 trillion based on the 1,350Mt of steel produced today, yet the average age of the global blast furnace fleet is only 13 years, with an expected technical life of 40 years.[50] More than half of global iron and steelmaking capacity is in emerging economies, with much of it only installed in the last 10 to 20 years. Accordingly, there is significant sunk investment in existing technology.

Capital cost for the construction of a new $H_2$ DRI-EAF is estimated to be broadly comparable to the cost of a new BF-BOF. However, this does not include capital for the construction of a hydrogen manufacturing plant — this could add a further US$375 million to US$950 million to the total cost of a new plant.

This means that a shift in Australian steelmaking technology requires significant investment. The total capital cost to replace Australia's existing BF-BOF steel production assets with $H_2$ DRI-EAF technology would be in the range of US$4 billion to US$6 billion, excluding hydrogen infrastructure.

The incentive to spend this capital is also challenged. There is no incremental volume or operational benefit expected from investing in $H_2$ DRI-EAF vs the BF-BOF technology — in fact, hydrogen-based DRI-EAF is expected to have 25%-35% higher operating costs than BF-BOF. There is, of course, technology development risk associated with investing this capital before the technology is proven commercially. This makes it very challenging for steelmakers to invest in emerging and breakthrough technology that will bring about material emissions reductions while remaining economically viable.

## 1.4 Steel pathways to net zero

$H_2$ DRI-EAF steel production is currently considered to be the most prospective long-term technology answer for large-scale decarbonising of the steel industry. However, the adoption of hydrogen-based steel will take many years, and a number of intermediate technology options will be required to reduce emissions while hydrogen-based technology matures and is commercially proven at scale.

Based on the multitrillion-dollar installed capital base of the global steel industry that is today based on BF-BOF technology and the criticality of steel to future global development, there is a significant incentive to find a technically and economically viable solution to decarbonising steel production without requiring a wholesale shift to $H_2$ DRI-EAF production. As such, the below pathway represents a view of how steel can be decarbonised based on the current view of technology, while still leaving open the potential for future breakthrough technology developments to change the pathway (for example, to decarbonise existing BF-BOF infrastructure).

Given this and other considerations in this report, the pathway to the decarbonisation of the Australian steel industry is based around three stages.

At each stage of the pathway the technical complexity and capital requirements increase from the previous stage, enhancing the potential risk.

**Table 5**
Pathway to the decarbonisation of the Australian steel industry

| Stage | Options |
|---|---|
| **Enhance** | Energy and resource efficiency:<br>• Renewable electricity<br>• Waste gas recovery<br>• Increased scrap utilisation<br>• Higher-purity ores |
| **Bridge** | Reconfiguration of existing assets:<br>• Biochar as pulverised coal injection replacement<br>• Hydrogen injection as partial coal substitute |
| **Breakthrough** | Implementation of breakthrough technologies:<br>• Hydrogen DRI-EAF |

## Case study: Existing emissions reducing efforts in the Australian steelmaking industry

The Australian steel industry has already started on the journey to decarbonisation and has implemented a number of emissions-reducing initiatives.

### 22 Turbo Alternator Project

Generation of electricity from the No. 1 Power House facility at the Port Kembla Steelworks ceased in July 2015, as it had become uneconomical due to the age and condition of equipment and the cost of natural gas. The No. 4 Alternator was one piece of equipment from the facility which was considered to have remaining life. The decommissioning of the No. 6 Blast Furnace in 2011 resulted in No. 21 and No. 22 Turbo Blowers at the No. 2 Blower Station becoming redundant. The steam turbines on these machines were in good condition, with the controls on No. 22 making it the more suitable for driving an alternator.

The aim of the project was to relocate the No. 4 Alternator to the No. 2 Blower Station and power it with the No. 22 Turbo Blower's steam turbine. The 'new' machine would be known as the 22 Turbo Alternator (22TA).

The benefits from this project include improved efficiency and reliability of electrical power generation within the steelworks, utilisation of excess by-product fuels which were previously flared to produce steam for the alternator (GHG reduction benefits) and reduction of electricity purchased from the NSW grid.

The 22 Turbo Alternator has been operational since September 2017.

(Continued)

Relevant data for the full financial years since then are:

| FY | Ave generation (MW) | Total generation (MWh) | NSW grid intensity (tCO2e/ MWh) | GHG reduction (tCO2e) |
|---|---|---|---|---|
| **2019** | 9.89 | 86,658 | 0.82 | 71,060 |
| **2020** | 9.42 | 82,555 | 0.81 | 66,870 |
| **2021** | 10.28 | 90,090 | 0.81 | 72,973 |

**Finley PPA**

In FY2018, BlueScope concluded an energy strategy review for its Australian operations. A key outcome included signing a seven-year, 233,000 megawatt hour (MWh) per annum Power Purchasing Agreement with ESCO Pacific for a new 500,000 panel solar farm at Finley, New South Wales. The agreement is one of Australia's largest corporate PPAs and equivalent to 20% of BlueScope's Australian purchased electricity demand.

## 1.5 Australia's future competitiveness with low emissions steel

High-level analysis suggests that $H_2$ DRI-EAF steelmaking is approximately 25%-35% more expensive on an operating cost basis today than traditional BF-BOF production.

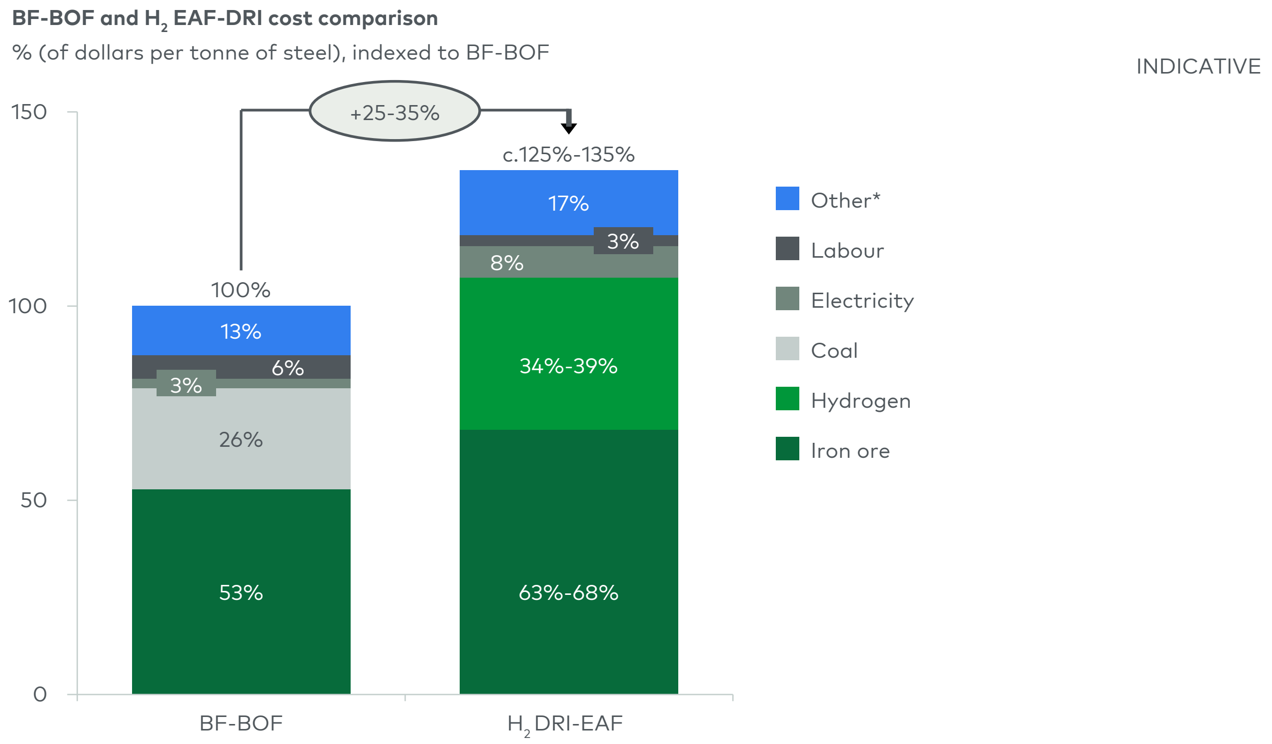
The differential in operating costs between BF-BOF and $H_2$ DRI-EAF production is largely driven by the price of coal and hydrogen, and the following chart provides the relevant sensitivities:

Over the longer term, Australia should have a number of natural competitive advantages in a decarbonised world that align it to being a competitive player in the global steel market, namely:

- A combination of solar and wind resources that should be able to provide Australia with an energy cost advantage
- Access to high-quality iron ore, albeit with some need to focus more on beneficiation of ores rather than extracting and exporting if BF-BOF ceases to be the primary global method of steel production
- Proximity to countries where steel demand is forecast to be high (e.g. Vietnam, Malaysia, Thailand and Indonesia)

There may also be potential to grow the Australian steel industry in the transition to net zero through exports. Previous analysis by the Grattan Institute has estimated that it may be more economical to produce 'green' steel in Australia and ship the finished product to countries with large downstream manufacturing such as Japan and Indonesia, which have inferior renewable resources, rather than ship the natural resource (i.e. iron ore) for further processing in those countries. Grattan estimated a 7% increase in market share in the global steel market would create an additional 25,000 jobs.

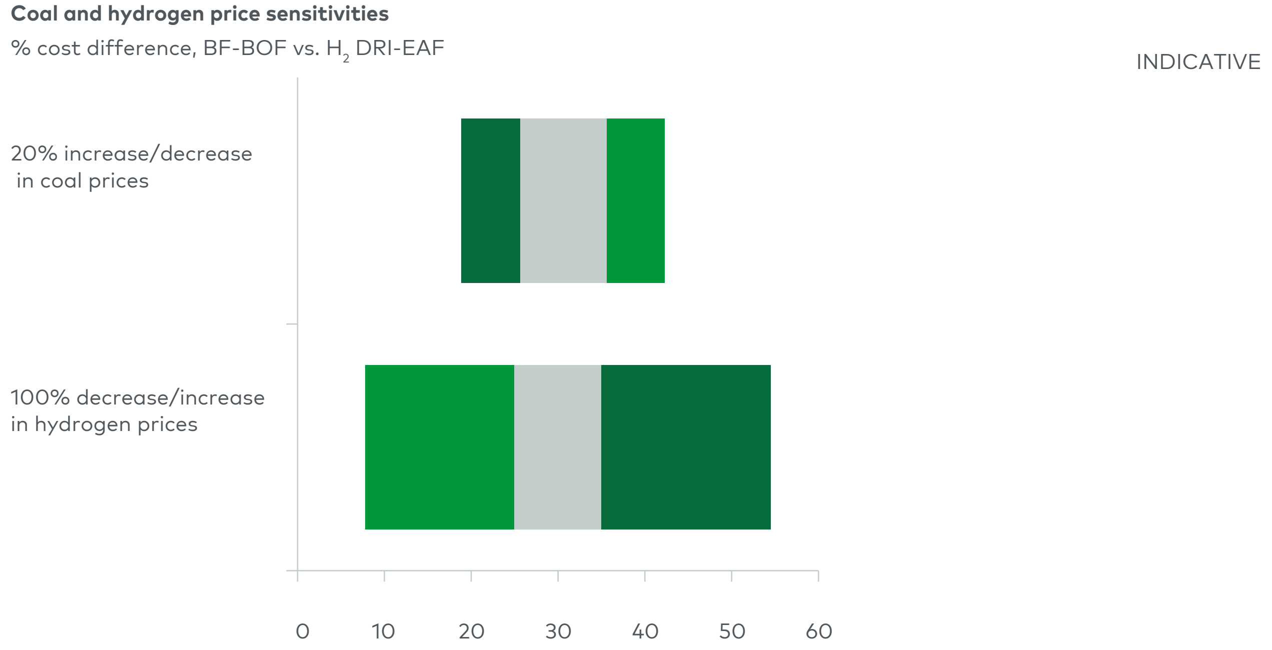
**Figure 20**
BF-BOF and $H_2$ DRI-EAF cost comparison



*Other includes ferroalloys, fluxes, electrodes, coal transport, iron ore transport, refractories, industrial gases, by-product credits, thermal energy Analysis as of July 2021

Source: Grattan Institute, Start with Steel; JP Morgan 2021 Green Steel; L.E.K. analysis

**Figure 21**
BF-BOF and $H_2$ DRI-EAF, coal and hydrogen price sensitivities



Notes: Analysis as of July 2021

Source: Grattan Institute, Start with Steel; JP Morgan 2021 Green Steel; L.E.K. analysis

However, maintaining and growing the Australian steel industry cannot be taken for granted — key enablers of Australian steelmaking competitiveness in a transition to net zero are:

- A policy environment that facilitates investment both in new steel capacity based on breakthrough technology and in emissions reduction upgrades during the remaining life of existing capacity
- Low-cost 'green' hydrogen, with development of a green hydrogen industry underpinned by high rates of renewable power generation and globally competitive delivered electricity costs

Equivalent treatment of domestic industry versus global competitors, recognising that in practice:

Not all regions are moving at the same pace towards green steel outcomes and emissions reduction obligations

Decarbonised steel is likely to be more expensive to produce than steel using existing technology

Some governments will provide high levels of support for their steel industries

- Increased differentiation between low emissions steel production and higher emissions steel and, where appropriate, government leadership in procuring low emissions steel that meets Responsible Steel™ global standards
- Developing raw material supply chains for future low emissions steel production

# Aluminium

Aluminium is an important material for modern economies and is used for a wide variety of applications in transportation, construction, electrical, consumer goods, and food and beverage sectors. It has a range of favourable characteristics, including its light weight, ease of shaping, high strength-to-weight ratio, corrosion resistance, electrical conductivity, heat dissipation, aesthetic properties and recyclability.

In the 2019-2020 financial year, alumina/bauxite and aluminium metal were Australia's eighth- and seventeenth-largest exports by value, respectively, and aluminium was Australia's highest-earning manufacturing export.[51]

The aluminium sector today is a significant source of carbon emissions, accounting for c.6% of Australian emissions[52] (c.2% globally).[53] Production of primary aluminium requires significant quantities of electricity (typically c.14MWh per tonne of primary aluminium smelted), with aluminium sometimes described as 'solid electricity'.[54]

## 2.1 Aluminium production today

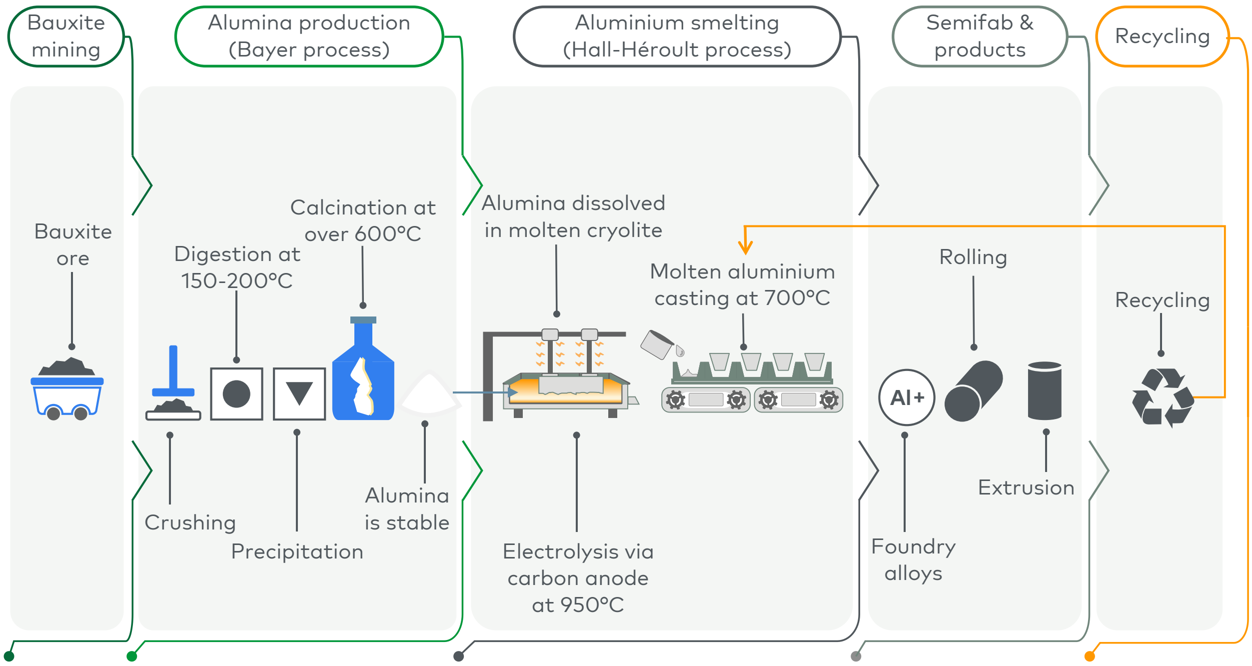
Aluminium is a metal that is produced from bauxite ore following two key stages.

The first stage is production of alumina from bauxite. Once extracted from the ground, bauxite is converted into alumina (aluminium oxide) using the Bayer process. Crushed bauxite is placed into a digester that dissolves the alumina content of the ore in a sodium hydroxide solution under pressure at 150°C-250°C. The solution is then cooled, and impurities and bauxite residues settle and are pumped into storage dams. The alumina-sodium hydroxide solution is filtered and then placed in a precipitator to form alumina crystals through mechanical stirring, seeded with previously precipitated alumina. The precipitated alumina is washed and then dried through calcination at more than 1,000°C, forming alumina — a dry, white aluminium oxide powder.

Alumina can be exported from an alumina refinery to aluminium smelters globally as either the dry aluminium oxide powder or the intermediate hydrate product that is produced prior to calcination.

In the second stage, alumina is converted into aluminium metal using electrolytic reduction in the application of the Hall-Héroult process. Alumina is dissolved in molten cryolite (sodium aluminium fluoride) in an electrolytic cell called a 'pot'. The pot is lined with carbon blocks and insulating bricks that form the cathode, while a carbon anode is used to conduct electricity into the pot. Multiple pots form a 'potline' where current flows into a pot from its positive anode, through the cryolite to the lining of the pot, and then on to the anode of another pot and throughout the rest of the potline in this fashion. The high electrical current flowing through the potline splits the aluminium and oxygen

**Figure 22**
Aluminium production process



Source: The Australian Aluminium Council, How Aluminium Is Made and Taylor Collision, Capral Limited (CAA) (diagram adapted)

from the alumina while maintaining the temperature of the process at around 950°C. Molten aluminium is periodically tapped from the pots and transported to a casthouse for casting into ingots, slabs, billets and t-bars at around 700°C.

Carbon emissions result from both alumina production and aluminium smelting:

- **Alumina production** releases 0.71t of CO2e for every tonne of alumina in Australia[55] (equivalent to c.1.4t CO2e for every tonne of primary aluminium produced), which is significantly lower than the global average of c.1.21t of CO2e per tonne of alumina.[56] Natural gas and coal are used to generate the heat and pressure required for digestion of the bauxite, and the volume of the bauxite and sodium hydroxide results in this step accounting for c.70% of alumina production emissions. The calcination process broadly accounts for the other 30% of alumina emissions, with the high temperatures for calcination achieved through the application of heat from gas-fired boilers.
- **Aluminium smelting** releases 12.57t of CO2e for every tonne of aluminium in Australia (on average), largely due to the generation of electricity required to produce the necessary current.[57] The carbon intensity of production reflects the carbon intensity of electricity generation in the proximate location to where the aluminium is produced and therefore varies across Australia (and the world). A smaller amount of direct emissions (including perfluorocarbon)

of 1.85t of CO2e per tonne of aluminium is released through the slow.[58] These anodes are made from petroleum coke and pitch and are often produced on-site today using thermal energy from natural gas.

Electrical efficiency is a key driver of the economic performance of an aluminium smelter, and producers periodically invest to apply more advanced potline technologies to improve efficiency. The modular nature of smelters with multiple potlines enables trials of new technologies and progressive upgrades to occur in existing plants.[59]

While being large users of electricity, primary aluminium smelters can also play a stabilisation role in electricity networks as a major source of network inertia. Smelters can quickly vary their energy consumption to respond to electricity market conditions and outages, and their demand can be an order of magnitude larger than any other major user on the network. Smelters can change the electrical current on potlines or rotate current through different potlines to reduce load, or rapidly shut down in an emergency to stabilise the grid. The ability for smelters to shed load does have limitations, as smelters cannot shut down for more than a few hours without ample warning, as the cryolite will turn solid and destroy the potlines.[60] Nonetheless, the flexibility of smelters to rapidly change their electricity demand provides the grid with an important stabilisation capability for use in emergencies.

## 2.2 Australian context for aluminium

Australia plays a critical role in the global market for alumina and aluminium, and the industry is expected to become more important as 'lightweighting' continues to impact transport and other industries in a net zero carbon world.

Australia is the largest producer and second-largest exporter of bauxite globally, the second-largest producer of alumina (but largest exporter), and the sixth-largest producer of primary aluminium. In 2020, Australia produced c.102Mt of bauxite (of which 37% was exported), c.21Mt of alumina (of which 84% was exported), and c.1.6Mt of aluminium (of which 90% was exported).[61]

Global aluminium prices are largely determined at the London Metals Exchange (LME) and have ranged from US$1,460/t to US$2,630/t over the last decade.[62] Regional premia can apply (e.g. Midwest, Japan) as well as product premia for shape and quality. Alumina pricing is also determined globally, with a number of benchmark indices (such as Platts, Fastmarkets and CRU) used as reference prices.

This important trade position means that significant carbon emissions are created in Australia for production that is then fabricated and used overseas.

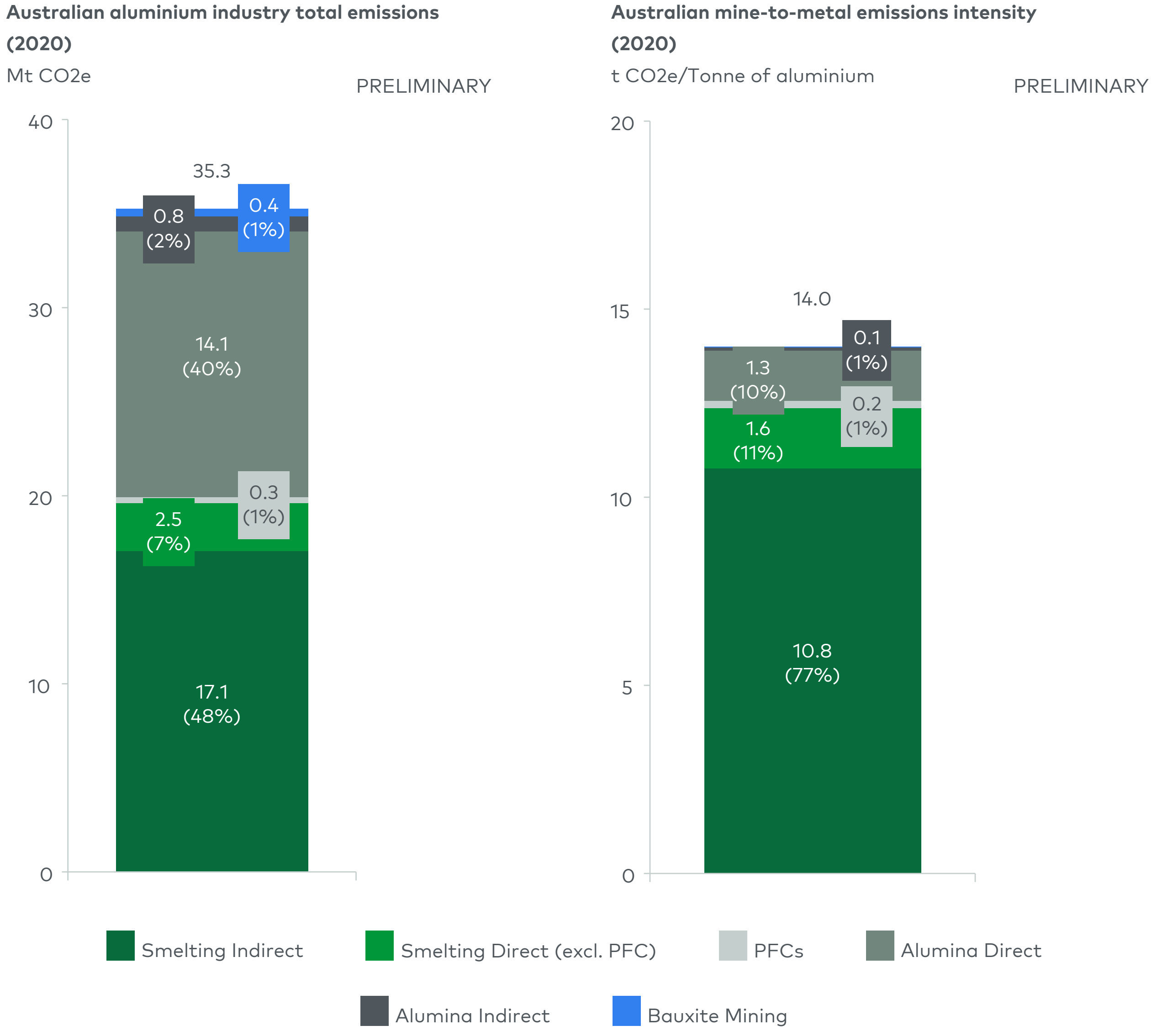
Australia's absolute carbon emissions for alumina and aluminium production are relatively evenly balanced as a result of Australia producing and exporting much more alumina than it consumes in aluminium production, while the emissions from Australian aluminium production on a per tonne basis (including emissions for the alumina used in this aluminium production) are much more heavily weighted to emissions from electricity used in smelting than is the case for combined emissions from all Australian alumina and aluminium production.

Australia has four primary aluminium smelters across four states:

- **Tomago Aluminium** is located at Tomago near Newcastle, NSW. It is an independently managed joint venture between Rio Tinto, CSR, and Hydro Aluminium, and has been operating since 1983. It produces 590kt of aluminium per annum, of which 90% is exported to the Asia-Pacific region.[63]

**Figure 23**

Australian aluminium industry total (left) and mine-to-metal emissions intensity (right)



**Australian aluminium industry total emissions (2020)**

**Australian mine-to-metal emissions intensity (2020)**

Source: Australian Aluminium Council, Australia's Aluminium Industry, March 2021 and Australian Aluminium Council, Sustainability Data 2000 to 2020

- **Boyne Smelter** is located at Boyne Island near Gladstone, Queensland. It is a joint venture led by Rio Tinto with six other parties and has been operating since 1982. It has a capacity of more than 500kt per annum.[64]
- **Portland Aluminium Smelter** is located at Portland on the south-western coast of Victoria. It is a joint venture between Alcoa of Australia (Alcoa Corporation and Alumina Limited), CITIC, and Marubeni Aluminium Australia,[65] and has been operating since 1986. It has a nameplate production capacity of 358kt per annum and produces ingot.[66]
- **Bell Bay Aluminium** is located at Bell Bay near Launceston, Tasmania. It was the first aluminium smelter built in the southern hemisphere and has been operating since 1955. It produces approximately 190kt per annum of ingot, block and t-bar.[67]

Aluminium is particularly well suited to being recycled because it loses none of its quality parameters during recycling and so can be recycled forever. Scrap remelt also has significantly lower carbon intensity than the creation of primary aluminium.

Australia has only one post-consumer aluminium remelt facility, the Weston Aluminium facility in Kurri Kurri, which produces a variety of products including deoxidants, base metal sows and Aldex. There is also a pre-consumer remelt facility within the G James operations for recovery of scrap from its own extrusions facility. More than 95% of Australian-generated[68] aluminium scrap is exported to remelt facilities overseas where the combined economics of energy costs, separation of aluminium grades and overall logistics costs make it more attractive. It is very difficult to use recycled material in primary aluminium smelters, as the contamination of scrap (including any water, oils and other contaminants) can be disruptive to production and may cause explosions.

Aluminium is also used in Australia to fabricate extruded products such as door and window frames, truck bodies, marine vessels, solar panel rails, and screening and fencing. Aluminium billet is heated to around 450°C and then extruded via a ram through a shaped die to create the desired profile shape. Australia has a domestic extrusion capacity of approximately 160,000 tonnes per annum. Capral Aluminium is Australia's largest extruder and operates manufacturing plants across five states. In contrast to Australia's export of aluminium metal, over 30% of Australia's extruded aluminium products are imported[69] and have been considered 'dumped' from some markets at below cost.

The Australian domestic extrusion manufacturing industry has consistently suffered injury from dumped imports. Anti-dumping and countervailing duties having been in place since 2010 on certain Chinese exporters, and currently there are dumping measures in place from certain exporters from China, Malaysia and Vietnam.[70] This unfair competition continues to affect industry members' ability to re-invest capital.

## 2.3 Challenges to transitioning to net zero emissions for aluminium

While the specific decarbonisation challenges for alumina and aluminium differ, there are several aligned themes in terms of developing a net zero pathway.

- **Alumina — zero emissions technologies for process heat and pressure.** The temperatures required for the Bayer process are high in an industrial sense, higher than the temperatures achieved by electrical heat pumps. Cofired coal-gas-based boilers and gas-fired calciners are the key technology used today to achieve the necessary process temperatures, resulting in emissions.
- **Primary aluminium — firm and competitive zero emissions electricity from the grid.** The major component of emissions for primary aluminium production is scope 2 emissions from electricity provided from the grid, and these generators and emissions are not controlled by the smelter. In NSW, over 75% of electricity in FY2021 was supplied by coal-fired power stations, resulting in relatively high levels of carbon emissions.[71] These emissions vary by state, with over 75% of Tasmanian electricity supplied by hydro and only 16% sourced from other markets and generators relying on fossil fuels. In other markets, such as New Zealand and Canada, electricity supplied is typically hydro dominated, resulting in significantly fewer carbon emissions per tonne of aluminium.[72,73] Many aluminium smelters globally are tied to captive power sources, some of which are fossil fuel fired, which poses a specific challenge for decarbonisation for those smelters[74] versus those tied to a grid that is decarbonising over time.
- **Primary aluminium — technologies to eliminate emissions from anodes.** A smaller component of aluminium smelting emissions results from the use of carbon-based anodes in the potlines that degrade over time as part of the electrolytic process.
- **Aluminium extrusions — firm and competitive zero emissions electricity from the grid.** The major component of carbon emissions from extrusion activities is in usage of electricity and gas, which is determined by the emissions of the electricity and gas supplied.

### a. Technology readiness

Decarbonisation of the electricity network supplying primary aluminium smelters is the largest potential opportunity for carbon emissions reduction, and the technologies for this transition are well known. Firming of the electricity supply is critical for the efficient operation of aluminium smelters.

The replacement of carbon-based anodes with inert anodes has been developed over a number of years. Rio Tinto and Alcoa have convened a joint venture called ELYSIS, which is expected to commercialise its inert anode technology by 2024. The joint venture has announced that the Alma smelter in Quebec will be used as the prototype facility for the ELYSIS technology.[75] Other competitors, including Rusal, have also begun test deliveries of inert anode technologies to reduce carbon emissions to less than 0.01t of CO2/tonne of aluminium.[76]

Replacement of cofired coal-gas boilers in alumina refining is more challenging, as the potential for conversion to renewable-based electricity is unlikely to achieve the required process temperatures. An additional challenge is that full electrification of an alumina refinery can result in demand from the refinery significantly outstripping supply of renewable power in some (but not all) regions. However, alternatives are being tested for both the bauxite digestion and alumina calcination processes.

For bauxite digestion, Alcoa of Australia has recently announced technical and commercial studies on a technology known as mechanical vapour recompression (MVR), supported by ARENA. Mechanical vapour recompression involves electrifying steam production to displace fossil fuel-derived thermal energy, substantially boosting production efficiency and lowering associated emissions. Should the studies be successful, Alcoa of Australia announced that it plans to install an MVR module on its Wagerup alumina refinery by the end of 2023. The technology has the reported potential for reducing carbon emissions in alumina refining by 70%, as well as reducing water use intensity. There is also some early-stage research for the use of electric boilers for bauxite digestion.[77] In March 2020, Brazil's largest aluminium producer, CBA, introduced a new wood-chip biomass boiler at its alumina refinery to replace its natural gas and oil-fired boilers, lowering emissions from 0.51t to 0.33t CO2e/tonne of alumina.[78] Norsk Hydro has invested in a fuel-switch project to replace heavy fuel with natural gas at its Alunorte alumina refinery in Brazil, with an estimated emissions reduction of 600,000t CO2e per annum.[79]

For alumina calcination, a potential process alternative is to replace the gas calciners with green hydrogen-based boilers. Rio Tinto is currently undertaking a feasibility study into this alternative with the support of ARENA. ARENA has also funded research, led by the University of Adelaide, into concentrating solar thermal (CST) technologies to generate the industrial process heat required for alumina smelting.[80] There are limited technology options for electrification of process heat for calcination; however, there is some early-stage research to enable retrofits to current systems to use electricity.[81]

### b. Delivery of cost-competitive energy

The delivery of cost-competitive and renewable electricity is the most important challenge for the primary aluminium sector to resolve in achieving a net zero outcome. On a per tonne basis, electricity is the source of over 80% of emissions for aluminium production in Australia and is therefore the largest potential area for reduction on a path to net zero.[82] Australia exports the majority of its aluminium into a globally traded market. As prices are largely set at the LME, profitability of an aluminium smelter reflects the cost position of each smelter on the cost curve. Profitability over the long-term price cycle will determine the ability of the smelter to remain operational.

### c. Reliable delivery of cost-competitive energy

However, cost-competitive energy must also be consistently available, and 'firming' of electricity delivery will be a critical component of decarbonisation for aluminium. Smelting is most efficient when operations are stable, and aluminium producers need a network where variability in electricity delivery can be removed. As mentioned above, aluminium smelters have an important role to play in network inertia and stability; however, this is a secondary role, as smelters see increased inefficiency with each electricity interruption.

Alumina refineries already provide some degree of demand response to electricity networks, and this capacity may increase should technologies to increase electrification of the alumina refining process be implemented.[83] The additional benefit of alumina refineries in demand response over aluminium smelters is that they do not have the same concerns regarding potline freezing.

### d. Rate of global industry decarbonisation

As the primary driver of carbon emissions for aluminium production is the underlying emissions of the supplied electricity, the differential rate of decarbonisation globally may impact the cost position of smelters differentially. While some smelters are already supplied by low carbon electricity, others, such as those in Australia, are ultimately supplied by higher carbon electricity generation. The decarbonisation transition period may disrupt any views of a level playing field across global regions, with distortions due to subsidies, trade barriers and overcapacity impacting the relative competitiveness of Australia versus its peers.

## 2.4 Aluminium pathways to net zero

As described above, the most important activity for decarbonisation of the Australian aluminium industry is the decarbonisation (and associated firming) of the electricity grid. However, there are other steps that will be important to achieving a net zero emissions position and can be taken by the aluminium industry itself in the shorter term.

## 2.5 Australia's future competitiveness with low emissions aluminium

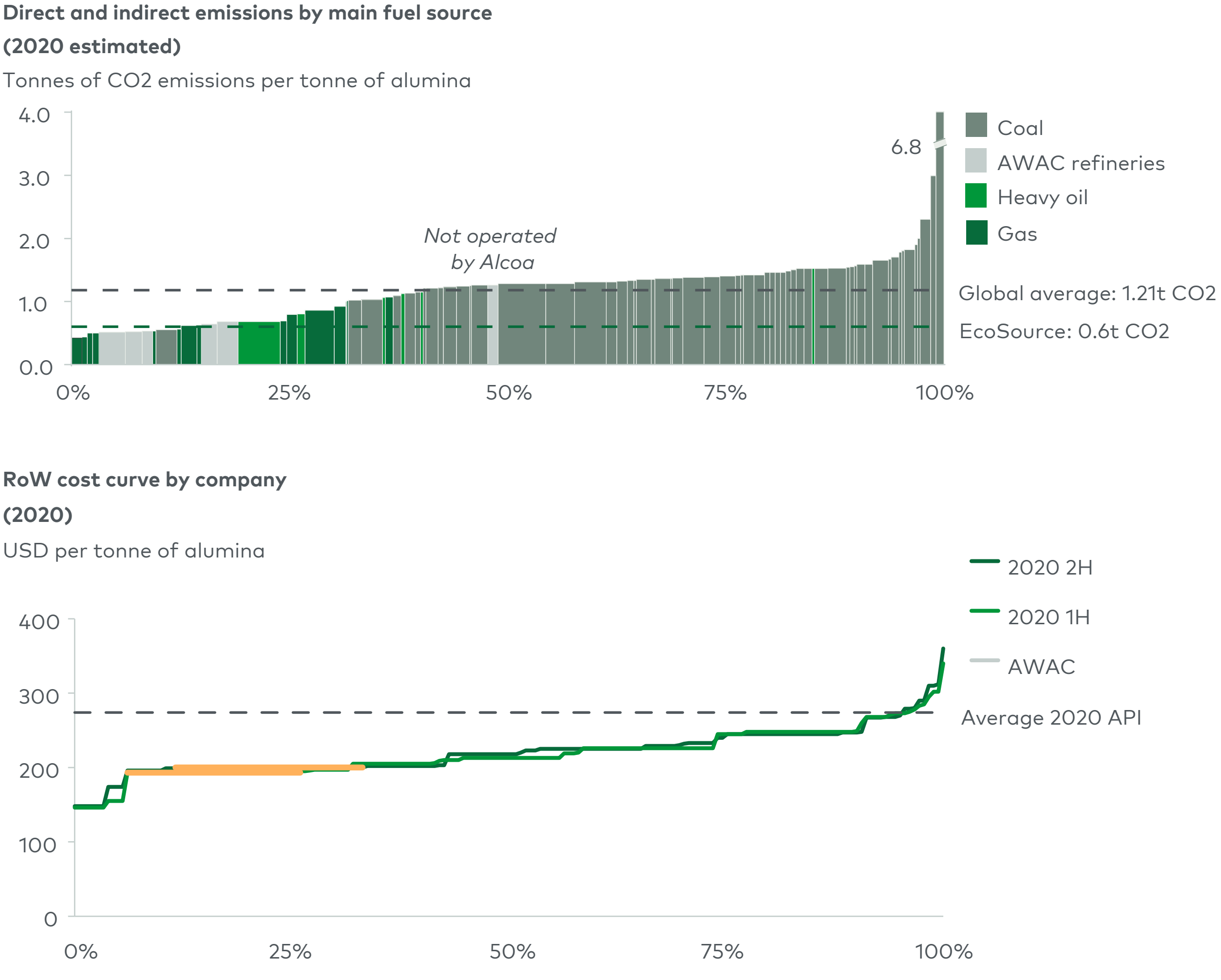
As discussed above, Australia's aluminium industry is heavily trade exposed. With 37% of bauxite, 84% of alumina and 90% of primary aluminium exported, the success of the industry is predicated on maintaining a competitive relative cost position versus global peers and maintaining absolute cost competitiveness against the cycle of global aluminium prices.

In today's environment, AWAC (Alcoa World Alumina and Chemicals), the world's largest bauxite miner and producer of

**Table 6**
Pathway to decarbonisation of the Australian aluminium industry

| Stage | Options |
|---|---|
| **Development of inert anodes*** | Development of non-carbon-based anodes for potlines and roll-out across the industry |
| **Alumina process adaptation** | Development and implementation of technologies that can reduce alumina process emissions, particularly on high-pressure or high-temperature processes such as:<br>• Digestion of bauxite<br>• Calcination of alumina |
| **Decarbonisation of the electricity grid** | Replacement of coal and gas-fired power generation with low carbon alternatives such as wind and solar, with firming capacity to ensure regular supply to aluminium smelters. This decarbonised electricity will also support carbon emissions reduction in the extrusion manufacturers. |

**Figure 24**
Alumina emissions intensity and world cost curve



Source: Alumina Limited, 2020 Full Year Results Presentation, 23 February 2021 (chart adapted); CRU, May 2021 alumina outside China, reports the lowest CO2 emissions intensity amongst major alumina producers.[84] AWAC's cash costs for alumina production in 2020 were in the lowest quartile of the global cost curve at $199/tonne of alumina.[85] Any differential increase in costs in response to further decarbonisation of the production process could impact the competitiveness of AWAC's alumina compared with its global peers.

The current cost curve for primary aluminium production is exceptionally flat in comparison to other global commodities such as iron ore (shows a strong cost increase in the third and fourth quartiles that insulates lower-cost producers from significant margin decline in low price environments). According to industry commentators, a cost increase of c.15% can shift an aluminium smelter's cost position from the attractive first quartile into the less attractive third quartile. And the cost curve is constantly changing in response to raw material cost levels, any production cost benefits achieved, exchange rates, new/mothballed capacity and production levels.

As over c.30%-40% of the costs for aluminium smelting are for electricity, the relative cost of electricity is often the determining factor for the cost curve position, and therefore profitability, of aluminium smelters.[86] Electricity prices for aluminium smelters are therefore highly confidential and commercial terms are not published globally. For the Australian aluminium industry to remain viable, it must therefore continue to source electricity at globally competitive prices.

Absolute profitability across the global price cycles can support a vibrant Australian aluminium industry. Over the last 10 years, prompt LME aluminium prices have ranged from c.US$1,440/t to c.US$2,630/t. At low aluminium prices, there is a substantial risk that third and fourth quartile aluminium smelters would be operating on a cash-negative basis. During the last non-COVID-19 price trough (2016), approximately 50% of aluminium smelters were believed to be cash negative.[87]

For Australian aluminium smelters to remain profitable across the cycle, competitive 'firm' electricity prices will be required. While the marginal cost of wind and solar generation is accepted to be the lowest available, future firmed energy prices for industry are still expected to sit at around $75/MWh electricity (average of Snowy FID NSW spot forecast[88] and Marinus NEM resource price forecast[89]). Investments in transmission and distribution could increase the cost of industrial electricity prices further. This is not a commercially competitive proposition for aluminium smelting in the current market. Firmed renewable electricity prices for aluminium smelting will most likely need to be less than $45/MWh to ensure profitability across the aluminium price cycle.

Differential policy response globally will provide the final driver of future competitiveness for Australia's aluminium sector. The pace of decarbonisation of the sector in Australia will most likely differ from international peers. Some competitors, such as those in Canada, already have lower carbon intensity due to their high reliance on renewable energy in the form of hydropower. Peers with captive fossil fuel power will find decarbonisation much more challenging. In some regions, including the US and EU, the application of carbon border adjustments is intended to account for carbon pricing for goods from countries that are yet to transition to low carbon electricity sources. Australian aluminium is typically exported to the Asia-Pacific where carbon border adjustments are not currently in operation. However, slow transition of the Australian electricity generation capacity towards an increasingly renewable base could result in alumina and aluminium exports being exposed to potential international border adjustments. Likewise, imports from countries with high carbon intensity could impact the ability of local extruders to compete should local transition to lower carbon energy be achieved rapidly and without the application of local border adjustments. The transitional period is difficult to map and will bring with it new competitive challenges for the Australian aluminium sector.

The aluminium manufacturing sector in Australia is dependent on a number of other stakeholders to ensure that it can remain competitive, profitable and vibrant within an Australian context. In summary, a number of key enablers must be achieved, including:

- Continued access to a globally competitive electricity pricing regime that allows it to remain in the lower two quartiles of the aluminium production cost curve
- Decarbonisation of the electricity generation base to allow access to renewable electricity sources, on a firmed basis, for primary aluminium and aluminium extruders and alumina refineries (once technical challenges are overcome)
- Continued support from government and research organisations that allows the industry to resolve the outstanding technical challenges for low carbon aluminium production, including new alumina technologies for bauxite digestion and alumina calcining, and hydrogen hubs
- Encouragement through policy for participants to work together as an industry to solve the carbon emissions issues that have been identified
- Positive engagement with the global trade community to ameliorate any impacts from foreign cross-border adjustments
- Equivalent treatment of domestic industry versus global competitors, recognising that in practice, not all

regions are moving at the same pace towards green aluminium outcomes and that some governments will provide high levels of support for their aluminium industries

- An efficient and effective Australian anti-dumping regime that does not require Australian manufacturers that are suffering harm to incur undue costs and effort to obtain remedies

# Ammonia

Ammonia is one of the world's most important chemicals and is used as a raw material in a broad range of applications. In 2020, 180Mt of ammonia was produced globally, making it the second most widely produced chemical commodity after sulfuric acid.[90] While approximately 75%-90% of ammonia is used for the production of agricultural fertilisers,[91] broader applications exist in explosives, pharmaceuticals and other chemicals. Without the crop yield made possible by ammonia-based fertilisers and chemicals, it has been estimated that the global population would be at least two to three billion less than it is today.[92]

Ammonia can also be used in energy applications. It can be directly used as a fuel in engines and gas turbines for shipping and power generation, and also as a carrier for storing energy and transporting hydrogen. With an energy density of 4.32KWh/L, ammonia has nearly double the energy density of liquid hydrogen.[93]

For every tonne of ammonia produced today using natural gas, 2.16 tonnes of carbon dioxide are emitted and over 30GJ of energy is used.[94] Globally, ammonia production generates over 420 million tonnes of CO2 annually and accounts for c.1.8% of CO2 emissions.[95] This requires c.3%-5% of global natural gas production and c.1%-2% of the world's annual energy supply.[96]

## 3.1 Ammonia production today

Ammonia ($NH_3$) is a colourless and pungent gas composed of nitrogen and hydrogen. The manufacture of ammonia from hydrogen and nitrogen today takes place in two main stages:

1. Manufacture of hydrogen via steam methane reforming (SMR) or autothermal reforming (ATR), with nitrogen either produced in the reforming process or via air separation
2. Synthesis of ammonia from hydrogen and nitrogen via the Haber-Bosch process

### 1. Manufacture of hydrogen and nitrogen

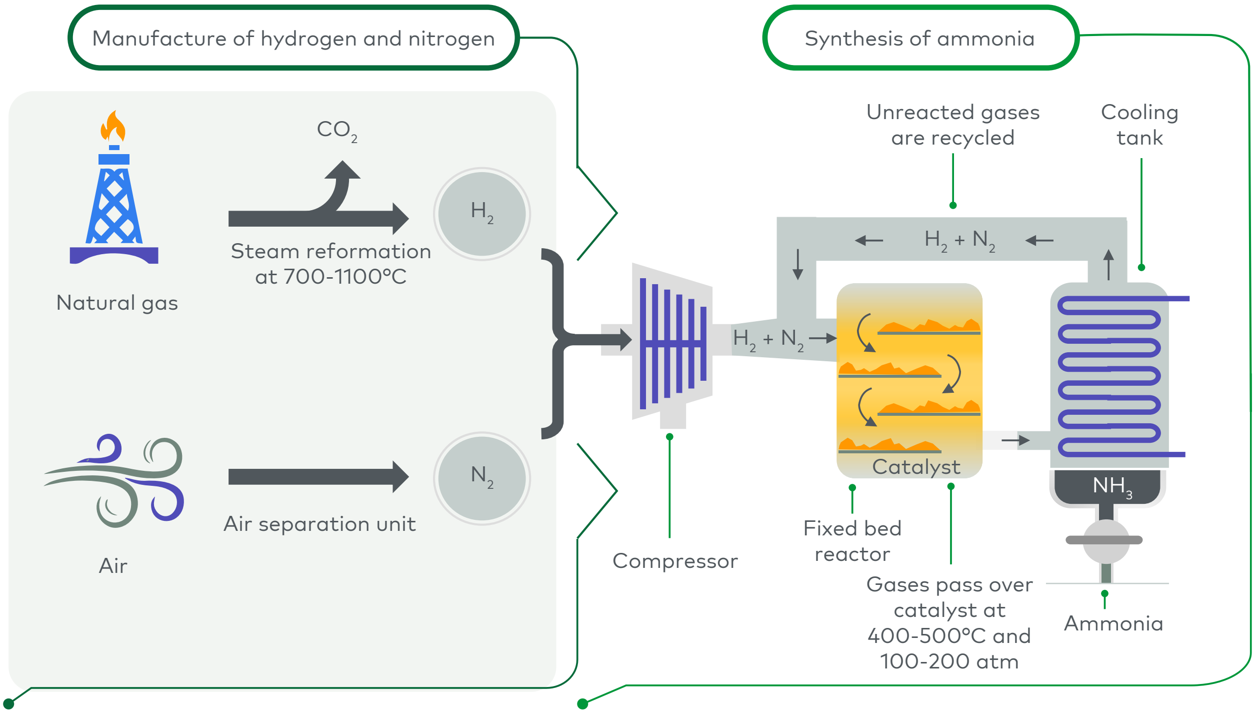
This SMR process consists of heating natural gas to between 700° and 1,100°C in the presence of steam and a nickel catalyst. The resulting endothermic reaction breaks up the methane molecules and forms carbon monoxide and hydrogen. The carbon monoxide gas can then be passed with steam over a catalyst to undergo a water gas shift reaction that obtains further quantities of hydrogen.

Nitrogen gas ($N_2$) is easily recovered from air by depleting oxygen via SMR or in an air separation unit.

### 2. Synthesis of ammonia

At the heart of the ammonia production process is the reaction between hydrogen and nitrogen in a fixed bed reactor. The

**Figure 25**
Ammonia manufacturing process



Source: Science Mag, Ammonia – a renewable fuel made from sun, air, and water – could power the globe without carbon, 12 July 2018 (diagram adapted)

gases, in stoichiometric proportions, are heated and passed under pressure over a catalyst. The process, known as the Haber-Bosch process, is highly energy intensive, operating at high temperatures (400°-500°C) and high pressures (100-200 atmospheres of pressure).[97]

Carbon dioxide emissions from the production of ammonia emanate from two key points. Over 60%[98] of CO2 emissions are from process gas, which is the by-product of hydrogen production. The remaining CO2 emissions (c.40%) are found in much lower concentrations in flue gas, the product of fuel combustion to power the process.[99]

## 3.2 Australian context for ammonia

Australia has seven ammonia plants with a total capacity of c.2.18Mt p.a., representing less than 1.5% of global production. Of Australia's total ammonia production:

- c.1.53Mt p.a. is 'captive', meaning it is utilised in an integrated manufacturing facility to produce other downstream nitrogen products such as urea (which is primarily used in the agriculture sector) or ammonium nitrate (primarily used in the mining industry)
- c.650kt p.a. is 'free', meaning it is either traded on the international market or sold directly into the agricultural or industrial segments

While the Australian ammonia industry is small relative to that in other countries, it is a significant employer and contributor to the broader economy across the Australian ammonia supply chain composed of:

- **Industrial gas manufacturing** — employing 2,036 people and generating revenue of $3.3 billion in 2019-2020
- **Basic inorganic chemical manufacturing** — employing 2,056 people and generating revenue of $1.8 billion in 2019-2020
- **Fertiliser manufacturing** — employing 3,960 people and generating revenue of $4.5 billion in 2019-2020

**Australian ammonia producers**

There are four main ammonia producers in Australia: Incitec Pivot Ltd (IPL), CSBP (a subsidiary of Wesfamers), Orica and Yara International. All four producers have significant existing capital assets deployed.

**IPL** has four plants located in Queensland (including one operated in a joint venture with CSBP):

- **Gibson Island** is a fully integrated nitrogen facility located in Murrarie, Queensland, and produces c.310kt p.a. of ammonia. The majority of the ammonia is used to produce urea, which is sold predominately into the agricultural markets. The remainder of the ammonia is sold directly into the agricultural and industrial markets. The site also has a 160t p.d. Liquid Carbon Dioxide Plant that supplies half the liquid CO2 in Queensland and is the main source for CO2 in carbonated soft drinks in QLD and northern NSW.
- **Phosphate Hill** is located in North West Queensland and produces c.200kt p.a. of ammonia. All of the ammonia produced at the site is used to manufacture c.975kt p.a. of ammonium phosphate fertiliser, which is predominately sold into the agricultural market.
- **Moranbah** is located 4.5km north-west of the town of Moranbah in Queensland, and is in close proximity to the Bowen Basin coal mines. Moranbah is a fully integrated nitrogen facility producing c.165kt p.a. of ammonia that is converted to produce 360kt p.a. of explosives-grade ammonium nitrate for the mining industry.
- **Queensland Nitrates Pty Ltd (QNP)** is located near Moura in Central Queensland and is a fully integrated nitrogen facility producing c.85kt p.a. of ammonia which is fully converted to produce 185kt p.a. of explosives-grade ammonium nitrate for the mining industry. QNP is a stand-alone 50/50 joint venture by Dyno Nobel (a subsidiary of IPL) and CSBP.

**CSBP** has two plants:

- **Kwinana** is approximately 40km south of Perth in Western Australia (WA) and is a fully integrated nitrogen facility producing c.255kt p.a. of ammonia, all of which is used to produce explosives-grade ammonium nitrate for the mining industry
- **QNP** — Noted above

**Orica** has a single plant at **Kooragang Island (KI)**, located in Newcastle, NSW. This is a fully integrated nitrogen facility producing c.360kt p.a. of ammonia. The majority of the ammonia is used to produce explosives-grade ammonium nitrate on site at KI and Orica's Yarwun ammonium nitrate facility in Queensland (ammonia transported via ship) for the mining industry. The remainder of the ammonia is sold directly into the fertiliser and industrial markets.

**Yara International** also has a single plant **(Yara Pilbara)** that is located on the Burrup Peninsula in WA and produces c.800kt p.a. of ammonia. Of the total production, c.150kt p.a. is supplied to the Yara Pilbara Nitrates Technical Ammonium Nitrate (TAN) plant, which is operated in a joint venture with Orica. This TAN facility converts ammonia into explosives-grade ammonium nitrate for the mining industry. The balance of Yara Pilbara's ammonia production is sold into the international ammonia market.

### Australian trade in ammonia

Australia is both an exporter and importer of ammonia, primarily as Australia has an ammonia surplus on the West Coast and a deficit on the East Coast as of 2019.

Australia's international ammonia trade in 2019 consisted of:

- Exports of US$74.7 million of ammonia, primarily to Taiwan (US$27.8 million), South Korea (US$20.6 million) and Thailand (US$19.1 million)[100]
- Imports of US$69.4 million of ammonia, predominately sourced from Saudi Arabia (US$56.2 million).[101]

Australia's ammonia price is linked to global ammonia prices through transport costs and marginal producer economics, that set the price across regions. Importation of ammonia requires specialised ships and storage tanks in-country.

## 3.3 Challenges to transitioning to net zero emissions

There are several challenges to achieving the goal of net zero emissions in the Australian ammonia industry.

### a. Technology readiness

There are currently three key options for the reduction/elimination of emissions from the production of ammonia.

**Process optimisation** options are the simplest form of carbon abatement and only reduce CO2 emissions of an existing process rather than eliminate emissions completely. Examples include access to renewable energy for site services (e.g. installation of solar power on-site), or improvements in energy efficiency (e.g. improved gas efficiency). The options are available today and are necessary interim steps as part of the long-term solution. Process optimisation has enabled the energy and emission intensity of ammonia plants to reduce by c.30% over the last 30 years.

**Carbon capture, use and storage (CCUS)** is most effective and efficient in reducing the emissions from a manufacturing/process operation which:

1. Has emission streams with a high concentration of CO2
2. Has few emission points for CO2 within a production facility
3. Is located in close proximity to a CO2 storage basin and/or end market for its sale and subsequent use (e.g. beverage manufacturer, enhanced oil recovery (EOR))

As such, CCUS is considered a potential option for the decarbonisation of ammonia production, as ammonia production emits a very high concentration of CO2 from the processing of gas to make hydrogen. Many ammonia plants already capture and use this pure CO2 stream to make urea and/or to sell into the food and beverage industry. However, this covers only c.60% of emissions, and the remaining CO2 emissions (c.40%) are in the much more diluted flue gas post fuel combustion. In addition, an ammonia plant producing 2,300 tonnes per day (current world scale) using one production line has typically only two primary points of CO2 emissions, those being the reformer vent and the process vent.

However, the location of an ammonia plant is significantly influenced by the availability of low-cost energy (e.g. gas), access to product distribution infrastructure and proximity to end markets (predominately agriculture). As a result, proximity to a CO2 storage basin and/or an end market for CO2 will vary significantly for each ammonia plant globally and will influence the applicability of CCUS in each case.

It should be noted that utilising CCUS does not result in the production of carbon-free ammonia. This is due to the difficulty in capturing CO2 from the fuel combustion process (i.e., flue gas). Without capturing these combustion emissions, it is currently estimated that CCUS at a conventional ammonia plant captures c.50%-70% of emissions from ammonia production. This results in the production of ammonia with low emissions.

CCU is fully commercial with numerous ammonia plants globally utilising this technology today (e.g. IPL sells CO2 from its Gibson Island ammonia plant into the industrial market). Geologic CO2 sequestration is a developing technology, incurs high cost for transport and storage components existing plant, and therefore is only viable for existing plants in certain situations (e.g. those in close proximity to a storage basin or CO2 pipeline), limiting its application to date.

**Hydrogen electrolysis (green hydrogen)** is the other major potential decarbonisation pathway for ammonia, as it involves replacing hydrogen produced using steam methane reforming of natural gas with hydrogen produced via electrolysis using renewable energy. The result is the production of carbon-free ammonia (green ammonia).

A number of green ammonia pilot projects have been announced globally, including the Yara Burrup project in Australia. The Yara

Burrup project is piloting the use of a solar-powered electrolyser to produce hydrogen that will feed into the existing plant operations to produce green ammonia. The initial phase of this project will pilot a 10MW electrolyser to generate <1% of the plant's total hydrogen requirements and produce 3.5k tonnes p.a. of green ammonia (total Yara Burrup plant capacity is c.800kt p.a.). The initial phase of the project is forecast to be operational by the first half of 2023, with plans to scale up to a 1,500MW electrolyser by 2030, which would produce close to all the green hydrogen required for the production of 800kt p.a. of emissions-free ammonia.[102]

The key development challenge for green ammonia is the time required to develop the water electrolysis technology to achieve the scale and cost competitiveness necessary for industrial application. One of the largest green ammonia projects currently in progress is set to produce 20k tonnes p.a. by 2023 using a 20MW electrolyser. This project at CF Industries' nitrogen complex in Donaldsonville, Louisiana, is at a complex that produces a total of c.4.3 million tonnes of ammonia annually — 20k tonnes of green ammonia would represent less than c.0.5% of total production on the site.

As such, the time required to scale green hydrogen technology for industrial application will have a significant influence on the timing for green ammonia production in Australia.

### b. Current regional energy price disparity

The competitiveness of an ammonia plant is significantly influenced by its energy costs (i.e. gas price), as these costs account for 70% to 80% of the cash costs of production.

The Australian ammonia industry is already disadvantaged in terms of its energy costs relative to international peers. Australian East Coast natural gas prices are currently estimated at $7-$9/GJ, significantly higher than the US$2-US$3/GJ paid by the largest ammonia producers in the world in the US and the Middle East. Today, ammonia can be imported from the Middle East, providing a c.50% operating cost advantage over Australian producers, and when freight from the Middle East to Australia of c.US$55/t is included, this still equates to a delivered cost advantage of c.20%.

This starting energy cost differential sets a challenge for the transition period as costs of decarbonisation are set to rise above current costs.

### c. Energy — incremental energy cost of decarbonisation

Both major ammonia decarbonisation options (i.e. CCUS or green hydrogen) require globally cost-competitive energy in the form of gas and/or low/no emissions electricity.

**CCUS** — electricity is required to power the capture and processing of emissions from ammonia production. It is estimated that 170,000MWh or 19MW of electricity is required to power a CCUS facility capable of capturing c.1.7Mt (required to capture CO2 from processing gas) of CO2 annually (assuming 800kt p.a. of ammonia and c.2 tonnes of CO2 captured per tonne of ammonia). With $75/MWh of electricity (average of Snowy FID NSW spot forecast[103] and Marinus NEM resource price forecast[104]), CCUS would add c.$40-$50/ tonne of ammonia (assuming 70% capture rate of CO2 and $23.50/tonne of CO2 for carbon distribution and storage) before any capital costs (e.g. CO2 distribution and storage).[105]

**Green hydrogen** — use of renewable electricity for hydrogen electrolysis will substantially increase electricity demand. The energy required to produce green hydrogen for the production of 800k tonnes p.a. of ammonia, equivalent to Yara's Burrup operations, would be c.7.6TWh. This is approximately 14% of the total renewable electricity generated in Australia in 2019.[106]

To achieve cost parity with Australian natural gas at $7-$9/GJ for the production of ammonia, hydrogen would need to cost c.$1.50-$1.80/kg, which would imply a delivered electricity price of $27-$33/MWh. This excludes the operational costs ($0.20 to $0.40/kg) for the electrolysis facility and any capital investment in the electrolysis facility or to convert the ammonia plant from natural gas feedstock.

The delivery of globally cost-competitive renewable electricity is critical and will be a key factor in driving the decarbonisation of the ammonia industry.

### d. Reliable delivery of energy

However, cost-competitive energy must also be consistently available, and 'firming' of electricity delivery will be a critical component of decarbonisation for ammonia. One of the key challenges with many forms of renewable energy is the intermittent nature of the supply, specifically for solar and wind. The issue for ammonia manufacturers is that the process of production is continuous and not batch. Thus, any interruption to the process of production either significantly affects its efficiency or materially impacts the manufacturing asset.

In isolation, renewable intermittent energy may appear cost effective, but firmed electricity supply is critical and can materially impact the overall cost.

### e. Rate of global ammonia industry decarbonisation

The rate at which the ammonia industry decarbonises globally will vary greatly by region and will be influenced by the availability of low carbon fuels (e.g. gas), the age of existing infrastructure, domestic carbon and trade policies and net ammonia trading positions.

The decarbonisation transition period may disrupt any views of a level playing field across global regions. Given that the Australian ammonia industry is highly trade exposed, the adoption of emissions-reducing technologies during this transitionary period will be influenced in practice by the level of incentives/ disincentives relative to other regions.

### f. Capital considerations

The decarbonisation of the Australian ammonia industry requires significant investment.

Any new capacity is expected to be developed using green hydrogen/ammonia technology. The capital cost for the construction of a new green ammonia plant is estimated to be broadly comparable to that of an SMR-based ammonia plant.[107] Hence for a new 800kt p.a. green ammonia plant the total capital is estimated to be between US$800 million and US$1.2 billion excluding the cost for renewable energy infrastructure. However, as noted above, green ammonia technology is yet to be proven at an industrial scale.

For Australia's existing installed ammonia production capacity, the capital cost for decarbonisation will vary depending upon the most appropriate pathway for each individual plant. However, these pathways are likely to follow a strategy of retrofitting existing assets with new technology as opposed to a wholesale reconstruction of a plant:

**CCUS** — involves retrofitting CCUS technology to an existing ammonia plant to capture the emissions, process them, and then either use or store the CO2. The capital cost for retrofitting carbon capture equipment to an ammonia plant process CO2 emissions is estimated at c.US$40 million to US$50 million. As mentioned above, for most process technologies, CCUS technology only captures c.60%-70% of the CO2 emissions from an ammonia plant and the incremental cost of capturing the remaining emissions from flue gases can be cost prohibitive. In addition, the above capital cost excludes any costs associated with CO2 distribution or storage. These costs on their own can be considerable given the need for pipelines to transport CO2 and storage infrastructure, etc. As a result, the total capital cost for the retrofitting of CCUS to an existing ammonia plant and enabling of use or storage will vary significantly and, in some instances, may simply be impractical due to the location of the plant relative to CO2 demand or storage locations.

**Green hydrogen** — requires decommissioning the SMR elements of the existing plant and installing a new electrolysis plant powered by renewable energy to produce hydrogen. The new electrolysis plant would be tied into the ammonia production elements of the plant.

The size and cost of the required hydrogen infrastructure are significant for this decarbonisation pathway. For example, to produce 800kt of 'green' ammonia would require c.140kt of hydrogen. This in turn will require approximately 900MW of electrolysis-based hydrogen production (assuming firm power and 100% utilisation), which is equivalent to the projected output of four of the world's largest currently planned electrolysis plants (e.g. in May 2020, Shell announced plans for a 200MW electrolyser in Rotterdam by 2023).[108]

The cost of hydrogen electrolysers today is estimated at US$500-US$1,400/KW,[109] which equates to a total capital cost of US$450 million-US$1,260 million for an 800k tonne ammonia plant. This excludes any capital costs associated with the decommissioning of existing SMR elements of the plant, and the retrofitting or tying in of the electrolysis plant to the existing ammonia plant or renewable energy infrastructure.

The decarbonisation of the Australian ammonia industry requires significant investment, and the incentive to spend this capital is also challenged. There would most likely be no or slight (c.5%) incremental volume or operational benefit from investing in either CCUS or green hydrogen — in fact, both technologies will add to the cost of producing ammonia, as discussed in Section 3.5 below. This could make it very challenging for ammonia producers to invest in breakthrough technologies that will bring about material emissions reductions while remaining economically viable.

## 3.4 Ammonia pathways to net zero

The below pathway represents a view of how ammonia production can be decarbonised based on the current understanding of technology. It is recognised that a new breakthrough technology could be developed which could change/alter the decarbonisation pathway for the ammonia industry. The pathway to the decarbonisation of the Australian ammonia industry is based around two stages.

At each stage of the pathway, the technical complexity and capital requirements increase from the previous stage, enhancing the potential risk.

## 3.5 Australia's future competitiveness with low emissions ammonia

High-level analysis suggests both 'green' hydrogen and CCUS will add to the cost of producing ammonia, with a CCUS pathway increasing costs by c.13% and a green hydrogen pathway increasing costs by c.123%.

**Table 7**
Pathways to the decarbonisation of the Australian ammonia industry

| Stage | Options |
|---|---|
| **Enhance** | Energy and resource efficiency:<br>• Renewable electricity<br>• Gas efficiency |
| **Breakthrough** | Implementation of breakthrough technologies:<br>• CCUS<br>• Green hydrogen |

## Case study: Existing emissions reduction efforts in the Australian ammonia industry

In line with its commitment to reducing its GHG emissions in 2020, IPL completed a $2.7 million feasibility study, supported by $0.9 million from the Australian Renewable Energy Agency. The study assessed the potential to use hydrogen produced from renewable energy (i.e. green hydrogen) to increase ammonia production at its manufacturing facility at Moranbah, Queensland.

The aim of the feasibility study was to determine whether green hydrogen can be produced at an industrial scale, and at a commercially competitive price.

Key findings:

- It was technically viable to produce green hydrogen at an industrial scale, and a facility was designed that could reliably provide a continuous supply of renewable hydrogen suitable for ammonia manufacturing. The design uses an off-grid (behind-the-meter) solar energy supply, with 160MW of electrolysis capable of producing approximately 25% of Moranbah's ammonia production.
- The study found that producing hydrogen at A$2.00 per kg to displace purchased ammonia would be cash flow positive. However, to generate a commercial economic return would require at least 60% of the upfront capital to be grant funded.

As such, commercial feasibility therefore requires:

- A price premium for green ammonia
- A reduction in renewable energy prices; and/or
- A supportive funding mechanism

Source: Incitec Pivot Limited

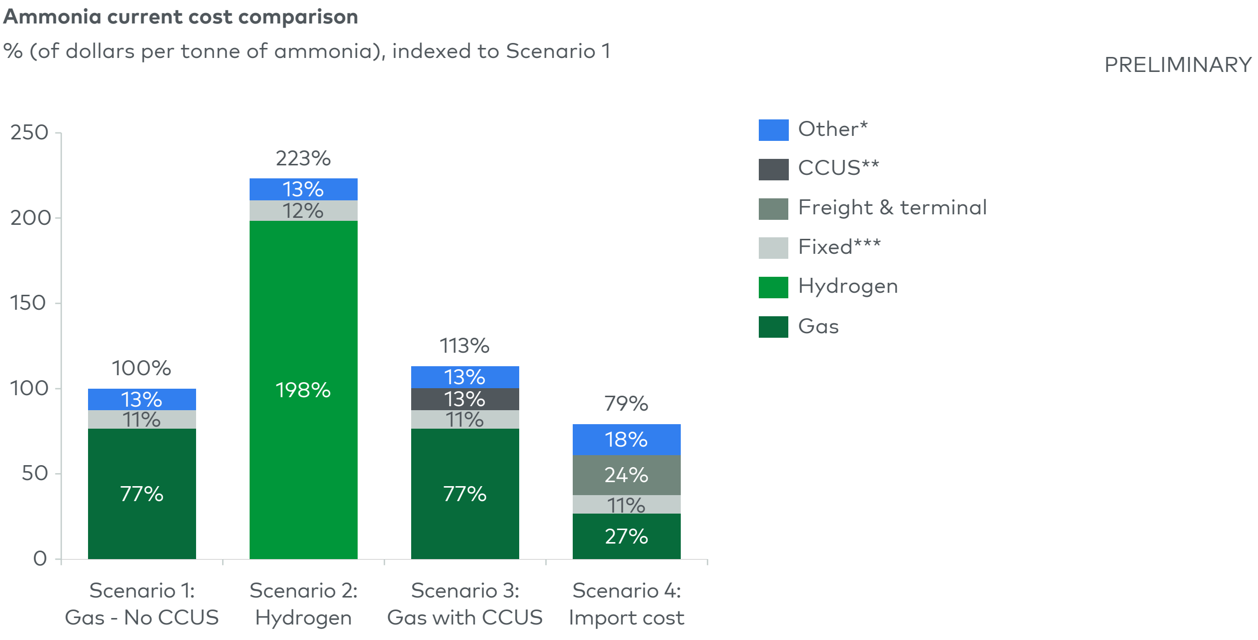
As noted above, Australian ammonia producers are already at a cost disadvantage relative to imports due to the energy price differential relative to international peers.

The decision about which technology option to adopt at a plant level will largely be driven by the costs of transporting and storing or using CO2 after capture (which may be infeasible in some locations) and the relative cost of energy at the time of investment (i.e. the cost of renewable electricity vs gas plus CCUS). The following Figure provides the cost sensitivities for both potential energy sources:

In Scenario 1: Gas — No CCUS, a 25% increase in the gas price from $8/GJ to $10/GJ increases the relative cost per tonne of ammonia (indexed to Scenario 1) to 119%, and conversely, a 25% decrease in the gas price to $6/GJ results in a decrease to 81%. In Scenario 2: Hydrogen, base case assumptions indicate that this processing approach has a relative cost of 223% versus Scenario 1. If we assume a 30% increase in the electricity price from $75/MWh to

**Figure 26**

Ammonia current cost comparison for a hypothetical 800kt plant located on the East Coast of Australia



Ammonia cost assumptions include electricity ($75.00/MWh), domestic gas ($8.00/GJ), $H_2$ ($4.05/kg), and import gas ($2.60/GJ)

*Other includes electricity costs, chemicals costs, conversion costs and other variable costs; **CCUS includes the cost of CO2 capture (assuming 70% is captured) and costs for the transport and storage of CO2; ***Fixed includes labour costs and other fixed costs. Analysis as of July 2021

Source: CSIRO, National Hydrogen Roadmap 2018, Australian ACCU spot price July 2021; Canadian Ammonia Procedures, Benchmarking Energy Efficiency and Carbon Dioxide Emissions; L.E.K. analysis

$100/MWh, this increases the relative cost per tonne of ammonia (indexed to Scenario 1) to 289%, and conversely, a 30% decrease in the electricity price to $50/MWh results in a decrease to 157%. In Scenario 3: Gas with CCUS, electricity costs are a small proportion of total costs and so the impact of a 30% change in electricity prices is negligible.

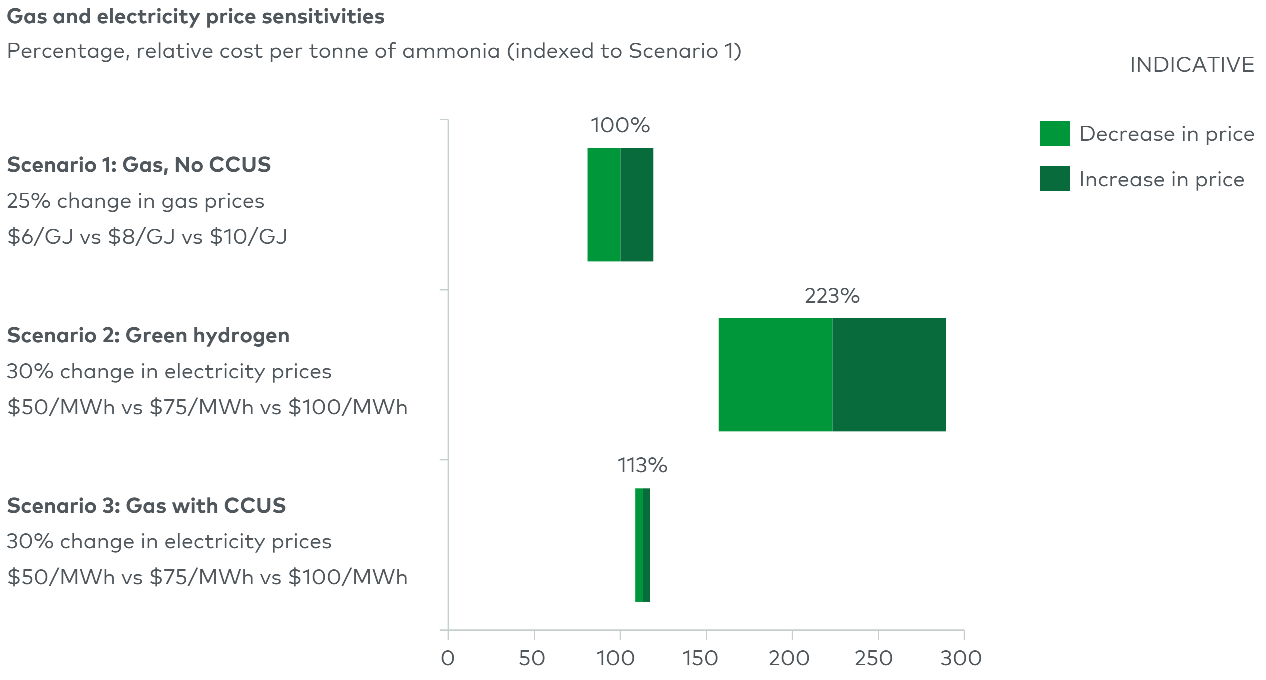
Despite the challenging economics today driven by Australian energy costs, Australia should have several natural competitive advantages over the long term in a decarbonised world that aligns it to being a competitive player in the global ammonia market, namely:

- A combination of solar and wind resources that should be able to provide Australia with an energy cost advantage
- Space available to scale and create renewable assets providing a cost advantage
- Proximity to countries where ammonia demand is forecast to be high (e.g. Japan)

There may also be the potential to grow Australia's ammonia industry given the potential application of ammonia outside of its traditional end markets like agriculture and mining. While green hydrogen is considered a potential key energy source in a decarbonised

**Figure 27**

Ammonia production gas, electricity and carbon price sensitivities



**Gas and electricity price sensitivities**

Percentage, relative cost per tonne of ammonia (indexed to Scenario 1)

Note: Analysis as of July 2021

Source: CSIRO, National Hydrogen Roadmap, 2018; Australian ACCU spot price July 2021; Canadian Ammonia Procedures, Benchmarking Energy Efficiency and Carbon Dioxide Emissions; L.E.K. analysis

world, there are challenges with its transportation and storage (e.g. high cost of transportation). Ammonia is considered to be an important potential alternative energy carrier given several benefits:

- Ability to store and transport — ammonia's volumetric density is 150% that of hydrogen, and these densities can be achieved at near-ambient storage temperatures
- Established logistics and end markets — a mature supply chain already exists given ammonia's widespread use today

There may also be other new applications for ammonia beyond energy storage and transport. Argus Media asks whether the 'green shift', or the trend towards sustainable, low carbon ammonia production, can create a billion-tonnes-per-year market — five times the size of today's ammonia market — based on the potential applications of ammonia in new markets such as marine fuels and power generation.[110]

However, maintaining and growing the Australian ammonia industry cannot be taken for granted and key enablers of Australian ammonia competitiveness in a transition to net zero are likely to be:

- A policy environment that facilitates investment both in new ammonia capacity based on breakthrough technology and in emissions reduction upgrades during the remaining life of existing capacity

- Low-cost 'green' hydrogen, with the development of a green hydrogen industry, underpinned by high rates of renewable power generation and globally competitive delivered electricity costs
- Equivalent treatment of domestic industry versus global competitors, recognising that in practice:
    - Not all regions are moving at the same pace towards green ammonia outcomes and emissions reduction obligations
    - Decarbonised ammonia is likely to be more expensive to produce than ammonia using existing technology
    - Some governments will provide high levels of support for their ammonia industries
- Strong differentiation of lower emissions vs higher emissions ammonia and, where appropriate, government leadership in procuring green ammonia and paying a premium that reflects the additional costs of low emissions ammonia production; this also requires contract terms (e.g. duration) that support the investment

# Cement and concrete

Cement, a dry powder manufactured from limestone, clay and sand, is a critical component of the infrastructure landscape and the construction sector. As a key input for concrete, the second most consumed material in the world after water, cement acts as a binder for crushed gravel, sand and water to give concrete its strength.[111]

Concrete is ideal for a broad range of use cases, as it is a durable, strong, inexpensive and adaptable construction material. Rising urbanisation, industrialisation and infrastructure development in emerging economies are expected to drive sustained increases in global cement demand. It is also important to recognise that concrete is an essential input into infrastructure enabling decarbonisation (for example, wind turbines).

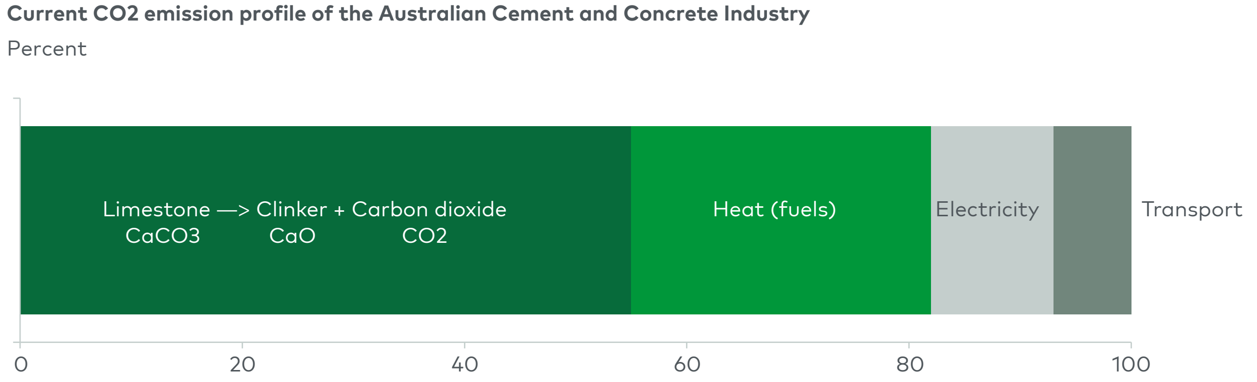
However, the cement and concrete sector is a significant user of energy and a major contributor to CO2 emissions. It is also widely considered to be a 'hard to abate' industry due to the fact that around 55% of emissions from the production of cement are 'process' emissions resulting from the production process itself rather than the energy used for production — these are emissions that would not be abated by ceasing to use fossil fuels as an energy source for production — see Figure 28.

In 2019, c.4.1 billion tonnes of cement and an estimated 26 billion tonnes of concrete were produced globally, accounting for c.8% of global CO2 emissions (c.1% of Australian CO2 emissions).[112,113,114] China is the world's largest producer, with cement production of c.2.4 billion tonnes in 2019, whilst the rest of the world produced 1.7 billion tonnes.

In 2018-2019, Australia produced c.10.4Mt of cement from c.5.6Mt of domestically produced and 4.1Mt of imported clinker (the difference is made up by gypsum or limestone added into the product) — see Figures 29 and 30.[115]

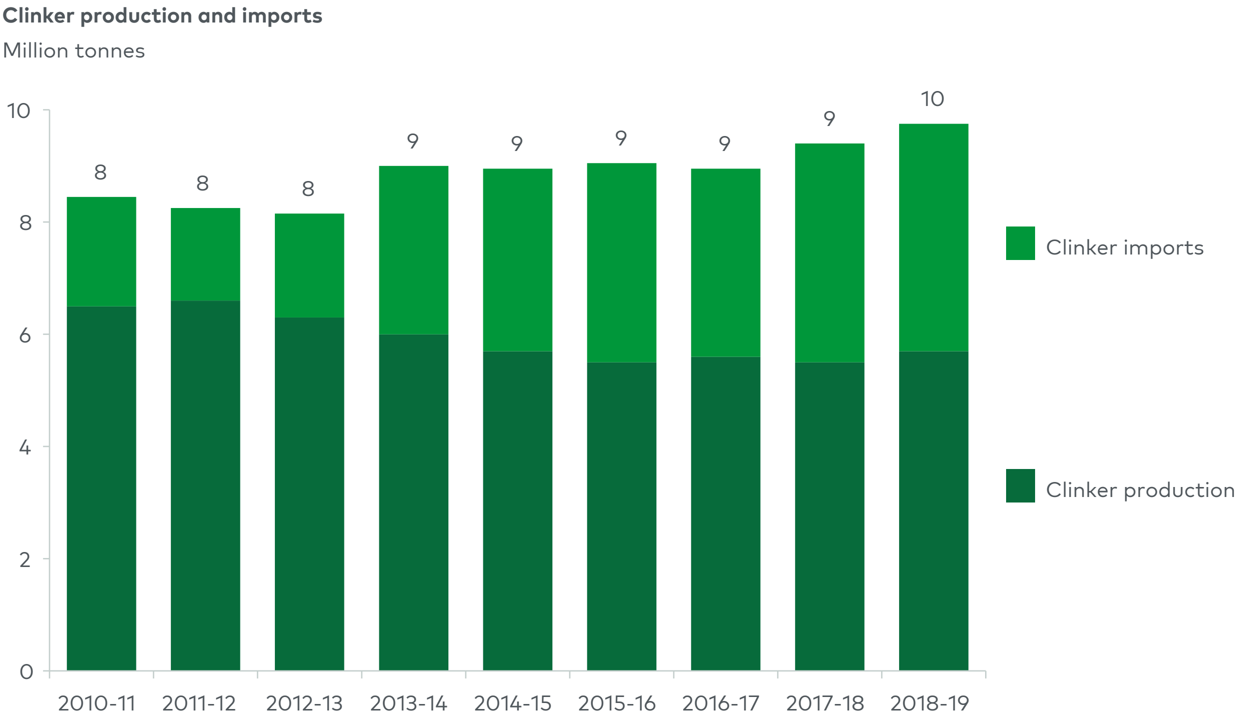
**Figure 28**

Current CO2 emissions profile of the Australian cement and concrete sector



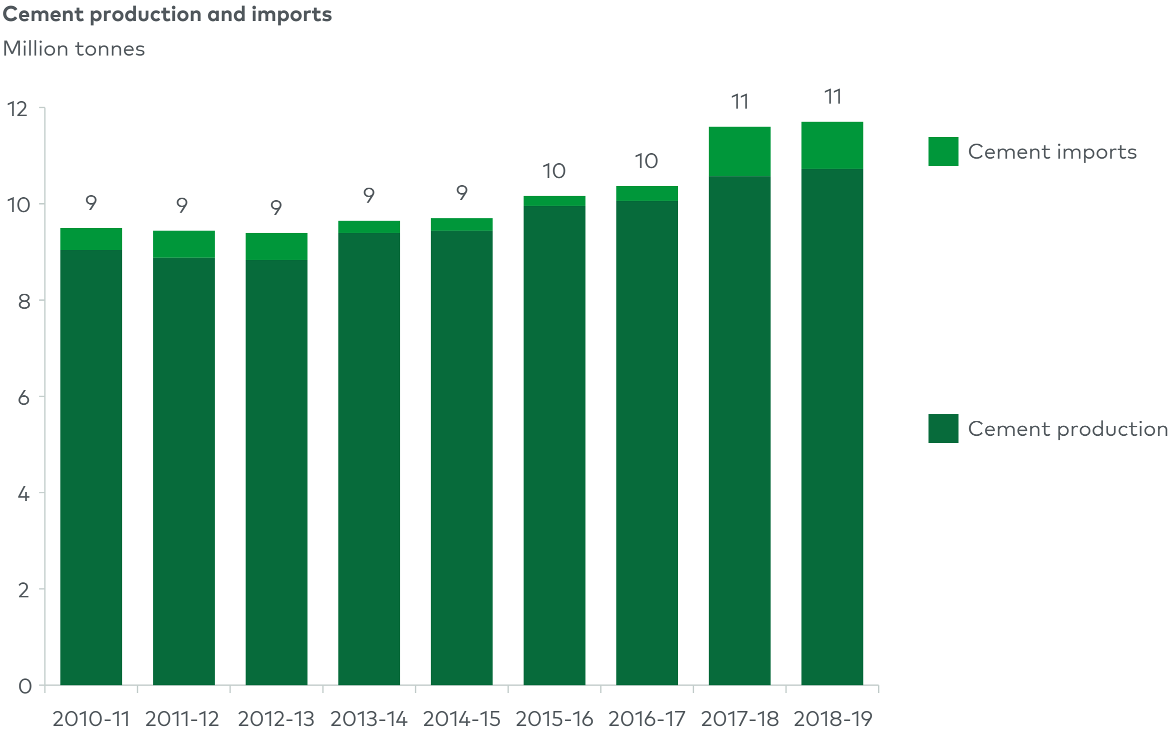
Source: VDZ, Decarbonisation Pathways for the Australian Cement and Concrete Sector, October 2021

**Figure 29**
Clinker production and imports



Source: CIF Survey, Australian Bureau of Statistics

**Figure 30**
Cement production and imports



Source: CIF Survey, Australian Bureau of Statistics

With China (and most other Asian countries) yet to implement a national carbon policy for cement production coupled with increasing imports over the last decade, Australian cement and concrete producers remain highly trade exposed into the future.

In Australia, total scope 1 and 2 emissions from the integrated production of clinker and cement were 5.1Mt CO2e in 2018-2019, excluding emissions for clinker production in countries exporting clinker to Australia for cement production.[116] The emissions intensity was 0.77t CO2e per tonne of cement produced from Australian-produced clinker (a precursor to cement) or c.200kg CO2e per cubic metre of pre-mixed concrete. [117]

Considering the emissions intensity of concrete and therefore taking into account emissions across the whole concrete value chain, supplementary cementitious materials (SCMs) such as fly ash and slag present further opportunities to lower the industry's overall carbon footprint.

While cement manufacture is an emissions-intensive process, the cement in concrete is able to absorb CO2 during its lifetime (recarbonations). Studies have estimated that up to between c.20% and c.40% of the CO2 emitted during the cement manufacturing process from 1930 to 2013 has most likely been sequestered in carbonating cement-related materials.[118] The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (2021) recognises that the uptake of CO2 in cement and concrete infrastructure (carbonation) offsets about one half of the carbonate emissions from current cement production.[119] This therefore presents opportunities in design and use of cement in concrete to lower emissions.

## 4.1 Cement production today

The manufacture of cement takes place in three main stages, with additional steps to produce concrete which can be used in construction applications.

### Raw material preparation

Limestone ($CaCO_3$), clay and sand are mined, and a precise mixture is finely ground into a 'raw meal' to use in clinker production. Emissions in this stage are limited and associated with mining machinery, transport and electricity for grinding.

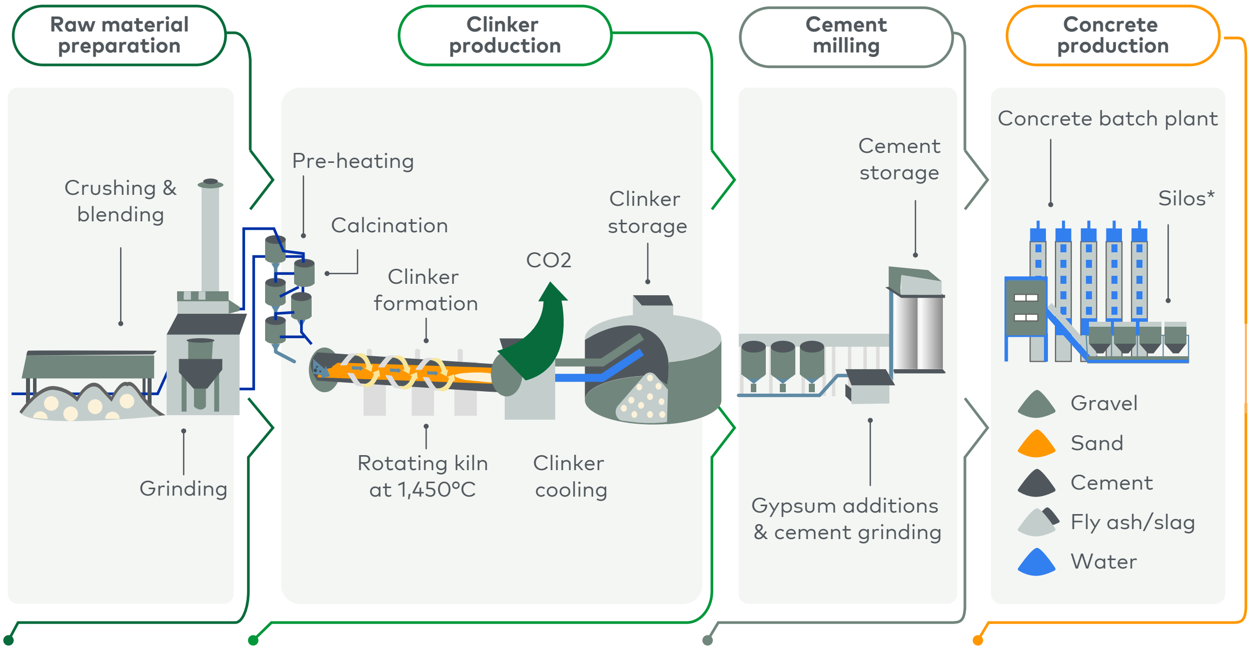
### Clinker production and cement milling

The ground raw meal is heated in a precalciner, where the calcination process occurs, before it is fed into a rotating kiln at around 1,450°C. The fossil fuels used to generate heat (e.g. coal or gas) produce 26% of the industry's GHG emissions.

The calcination of limestone removes carbon dioxide from the limestone, releasing CO2 in the process. This process creates 'clinker' — small, hard lumps or nodules of calcium silicates of a similar size to marbles. The CO2 process emissions from this step account for 55% of the industry's GHG emissions,[120] and it is these emissions that make cement a 'hard to abate' industry.

**Figure 31**

Cement and concrete production processes



*Australian concrete batch plants are typically configured with only two silos (cement and fly ash) or three silos (cement and fly ash and slag) and may not be able to easily accommodate additional silos for other inputs; this is different from markets like Europe where facilities have been designed to accommodate multiple blended cements

Source: Beyond Zero Emissions, Zero Carbon Industry Plan Rethinking Cement, August 2017 (diagram adapted)

The clinker is cooled and ground into a fine powder in a cement mill, and is mixed with gypsum and usually limestone mineral addition to form cement.

The remaining emissions are indirect; 12% relate to electricity use for other parts of the plant including cement milling machinery and for activities after the cement facility to use cement in concrete batching plants.

Transport emissions for the cement and concrete sector are estimated to be c.7%.

### Concrete production

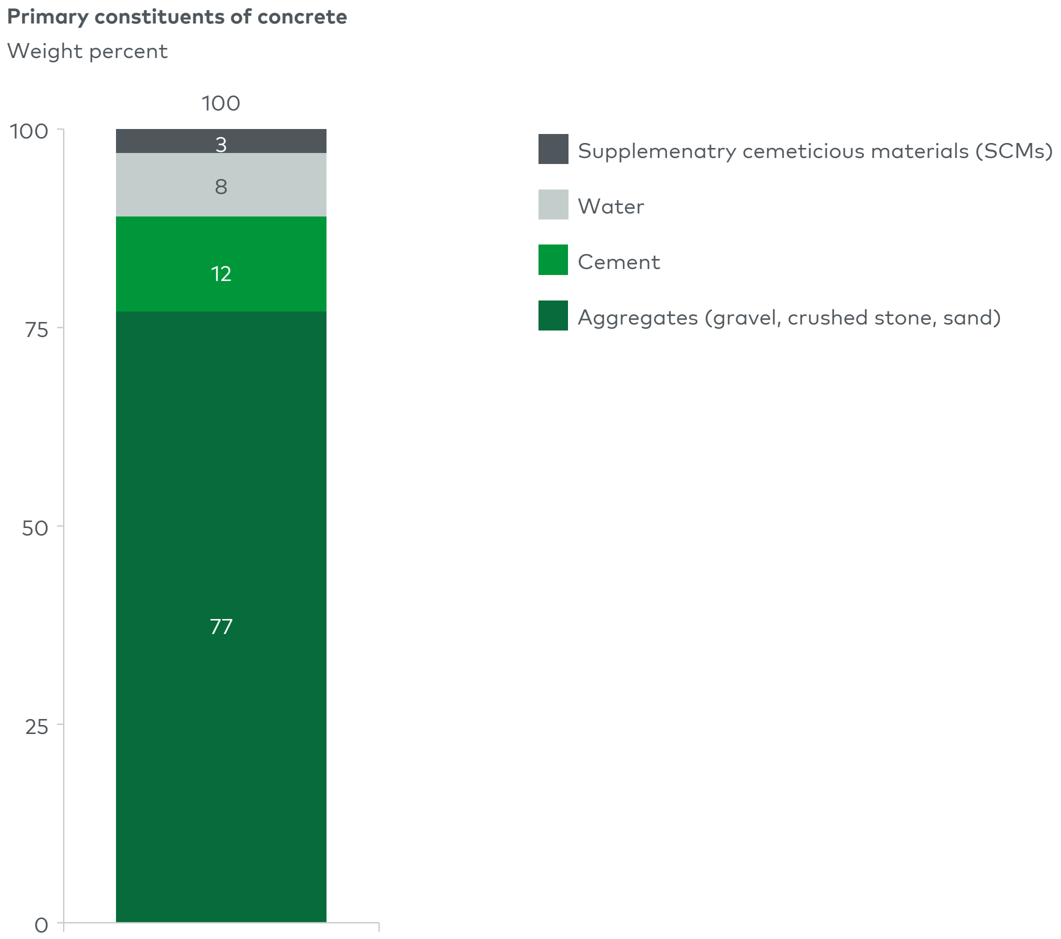
Concrete needs to be produced close to locations where it will be used, as it hardens from a plastic state over a relatively short time to form a hard, durable material.

In the Australian market, about 90% of all concrete is made in over 1,500 batch plants that are used to produce ready-mix concrete close to market to then deliver it in an agitator truck. The balance is used in factories which prefabricate components for use in construction and infrastructure applications.

Ready-mix concrete combines gravel (aggregates), sand, cement, water, chemical admixtures and other supplementary cementitious materials (SCMs) such as fly ash or slag in specific proportions into agitator trucks. Concrete is then delivered in these trucks to a construction site on a just-in-time basis to be cast.

A typical concrete mix is depicted in Figure 32.

**Figure 32**
Primary constituents of concrete



Source: VDZ, Decarbonisation Pathways for the Australian Cement and Concrete Sector, October 2021

## 4.2 Australian context for cement and the importance of concrete

In 2018-2019, Australia produced c.10.4Mt of cement from c.5.6Mt of domestically produced and 4.1Mt of imported clinker (the difference is made up by gypsum or limestone added into the product).[121] Around 70% of Australian cement is used for ready-mix concrete, while 5%-10% is sold as bagged cement, 15%-20% is used in precast applications, and c.5%-10% is used for mining and road stabilisation purposes.

The Australian cement industry is a key employer with over c.1,300 people directly employed in Australia, with an additional c.5,000 people employed in directly related downstream production and distribution markets within the cement and concrete industry.[122]

Australia's growing infrastructure and construction market has led to an increased demand for cement that is increasingly met with imports. In 2018-2019, Australia imported c.0.9Mt of cement to supplement cement produced from domestic and imported clinker.[123] Major sources of imports include Japan (c.38% of volume), Indonesia (c.30%), Thailand (c.15%), Malaysia, and Vietnam.[124]

Due to the relatively homogenous nature of the basic product, Australia's energy-intensive cement industry is trade exposed and competes against imports that can be substituted for domestic product with comparative ease. Clinker overcapacity has been and remains significant in key markets supplying imports to Australia, growing from c.450Mt in 2010 to c.1,780Mt in 2018.[125] Despite overcapacity, clinker kiln investment is continuing across the Asia-Pacific region, and Australian clinker typically has lower embodied carbon than other clinker produced in the region.

There are five integrated cement manufacturing facilities in Australia that produced c.5.6Mt of clinker used in Australian cement in 2018-2019 (see Figure 33).

Australian imports of clinker have substantially increased to c.4.1Mt in 2018-2019 from c.1.9Mt in 2010-2011. There are 11 stand-alone cement mills that are predominately used to grind imported clinker.

**Figure 33**
Location of integrated cement manufacturing sites

Source: Gladstone Development Board, July 2018; CemNet, The Global Cement Report (13th edition), July 2020; Boral, Boral Cement Works Berrima, July 2021; Geocycle History, July 2021

**Table 8**
Australian stand-alone cement mills

| Location | Ownership | Annual capacity (Mt p.a.) |
|---|---|---|
| **Wynnum (QLD)** | Sunstate (jointly owned by Boral and Adbri) | 1.50 |
| **Kwinana (WA)** | Cockburn (Adbri)* | 0.36 |
| **Darwin (NT)** | Northern Cement (Adbri) | 0.25 |
| **Port Kembla (NSW)** | Cement Australia | 1.10 |
| **Port Kembla (NSW)** | Morgan (Adbri) | 0.70 |
| **Maldon (NSW)** | Boral** | 0.88 |
| **Kooragang (NSW)** | Boral | 0.11 |
| **Waurn Ponds (VIC)** | Boral | 0.75 |
| **Bulwer Island (QLD)** | Cement Australia*** | 1.20 |
| **Perth Naval Base (WA)** | BGC Cement | 1.30 |
| **Pikenba (QLD)** | Wagners Cement | 1.30 |

*Adbri will consolidate Kwinana and Munster to boost annual production capacity by 400kt to 1.5Mt; **Maldon operated using clinker from the Berrima kiln; ***Bulwer Island operates using both Gladstone and imported clinker
Source: CemNet

In recent years, the cement market has seen several new players introducing additional cement import terminal capacity (or, in the case of SA Premium Cement, importing in bulka bags). These terminals use vacuum-based open-hold ship unloaders that can directly unload cement from standard bulk carriers rather than requiring specialised pneumatic cement carriers and associated infrastructure that have traditionally been used for shipping cement around Australia.

The entry of new suppliers and increasing imports demonstrates the potential for 'carbon leakage' if Australian emissions reduction efforts adversely impact the competitiveness of Australian clinker and cement production.

There are several inherent differences between the cement supply chain in Australia and other international markets which will affect the emissions reduction pathways:

- The Australian cement supply chain is configured with a higher reliance on coastal shipping by pneumatic vessels and a greater proportion of clinker imports than other markets, necessitating safety capacity in

**Table 9**

Australian cement import terminals

| Name | Location | Ownership | Annual capacity (Mt p.a.) | Features |
|---|---|---|---|---|
| **Southern Cross Cement** | Brisbane (QLD) | Jointly owned by Brickworks, Neilsen Group and Neumann Group | 0.20Mt[125] | Southern Cross Cement provides cement to Brickworks' Austral Masonry and Bristile Roofing operations in Brisbane, and uses a 12,000t/day ship unloader[126] |
| **East Coast Cement** | Kooragang Island (NSW) | Vue Australia (Barro Group controlled company) | 0.3Mt, receiving imports from China[127] | In September 2016, East Coast Cement announced the commissioning of storage capacity of 40,000t of bulk cement, reviving a petroleum coke and alumina storage facility that was set for closure. It serves independent concrete operators, construction projects and mining operations in the region[128] |
| **Gunlake Concrete** | Sydney (NSW) | Falcon CP (NSW Cement Products) | Not publicly available | Gunlake positions itself as the largest local independent supplier of concrete and quarry products in NSW. In October 2019, GrainCorp commenced a partnership with Falcon to modify four silos to store cement powder imports. In March 2021, GrainCorp announced a move to convert its existing port terminals to use them for woodchips, cement and fertilisers[129,130] |

the high-volume supply chains and making configuration changes more costly than in other markets. Intermediate storage facilities (depots) are used extensively in Australia, while European and North American markets often employ direct delivery to end users.[131]

- SCMs often require additional capital investment in infrastructure in Australia, as SCMs are generally blended into concrete at batch plants, while Europe tends to blend SCMs with cement at the point of manufacture in order to supply a blended cement product to batch plants. While the European model reduces infrastructure requirements to store SCMs at batch plants, it also reduces flexibility to easily differentiate products for customers and applications compared to the blend-at-batch-plant model used in Australia and North America. This means that it is critical for any comparison between markets to focus on the clinker factor of concrete in order to consider emissions across the full concrete value chain and recognise the strong utilisation of SCMs in concrete in Australia.
- There is a distinct opportunity for coordinated emissions reduction across the concrete value chain in Australia, as key players in the Australian market are generally vertically integrated between cement and concrete. While this vertical integration is common in Europe and North America, it is less common in Asian markets, as cement is often supplied in bags rather than bulk.

## 4.3 Challenges to transitioning to net zero emissions

There are several challenges to achieving the goal of net zero emissions in the Australian cement industry and broader concrete value chain that are not simply addressed by adopting general zero-emissions technologies used in other sectors like electrified transport or renewable electricity for current electricity requirements.

### a. Technology readiness and choices

Significant research and development are being undertaken globally to identify and implement technologies to reduce/eliminate the emissions from the manufacturing of cement. The potential approaches to emissions reduction vary in their technology maturity (readiness), complexity, cost and level of CO2 reduction. Five main approaches for emissions reduction are set out in the table below.

**Clinker substitution technologies** can lower energy use, reduce pollutants, reduce raw material consumption and enable the utilisation of industrial waste products. Supplementary cementitious materials (SCMs) such as fly ash, slag and increased limestone (ground and unburnt) can be used to supplement cement from clinker, reducing the clinker content in cement without adversely impacting the performance:

- **Fly ash**, a by-product of thermal coal combustion in power generation, is commonly used as a 20%-30% cement replacement in cement and concrete, depending on the desired performance of the concrete and the quality of the fly ash.[133] The addition of fly ash improves the durability, flexibility and impermeability of concrete, whilst still maintaining late age strength performance. Replacing one million tonnes of Portland cement with fly ash would result in an emissions reduction of approximately c.0.67Mt to 1Mt CO2-e, depending on the source of the clinker.[134]
- **Ground granulated blast furnace slag**, a non-metallic by-product of the iron and steelmaking sector, can be used as a 30%-65% cement replacement in cement and concrete.[135] Like fly ash, ground granulated blast furnace slag improves the durability of concrete whilst still maintaining late age strength performance.
- **Silica fume**, a by-product of producing silicon metal, is also used as a partial replacement for cement in concrete and increases the compressive strength and durability of concrete. Substitution rates of silica fume are generally very low, with key uses including for avoiding excessive water demand in concrete and for other specific applications.
- **Limestone,** when ground finely, can be used to partially replace clinker in cement and concrete.

The availability of these by-products (other than limestone) may diminish in the future as coal-fired power plants retire and new decarbonised steelmaking technologies replace BF-BOF steelmaking.

**Table 10**
Potential emissions reduction approaches for cement

| **Approach** | **Clinker substitution** | **Thermal and electric efficiency** | **Alt. fuels and renewable energy** | **Carbon capture, use and storage (CCUS)** | **Other breakthrough technologies** |
|---|---|---|---|---|---|
| **Description** | Reduce clinker ratio of concrete by substituting a proportion of clinker with supplementary cementitious materials (SCMs) for some binder requirements | Deploy state-of-the-art technologies in new capacities and retrofit energy-efficient equipment when economically viable | Use alternative fuels and raw materials with a higher share of biogenic wastes in place of fossil fuels | Capture CO2 emissions from cement kilns, compress into a liquid and either store in deep underground reservoirs or use it for other industrial processes | Use alternative binders for clinker substitution (lithium, natural pozzolans, limestone calcined clays), fly ash dam remediation for concrete-grade fly ash, and green hydrogen fuel in production (partial substitution) |
| **Examples** | • Current SCMs include blast furnace slag, fly ash, silica fume | • Upgrading kilns and equipment so less energy is needed to produce cement<br>• Changing plant design, upgrading motors and mills | • Using by-products of industrial processes<br>*e.g. Wood waste and other biomass can substantially reduce emissions, while solvents, carbon powders, used oil and spent pot liners can reduce emissions* | • Capturing and storing CO2 for industrial uses<br>• Capturing and storing CO2 from across the cement production process | • Limestone calcined clays could reduce emissions by at least c.20% [131]<br>• European plants have piloted the use of hydrogen in the kiln as a partial replacement for natural gas |
| **Timing (years)** | Now | Now | Now | 5-10 | 10+ |
| **Status** | Technology is readily available, but there are significant opportunities to optimise cement standards, asset standards and utilisation of different cement types to reduce clinker in concrete | c.98% of Australian manufactured clinker is now produced using highly efficient suspension preheater precalcination technology | Currently, alternative fuels meet c.18% of the total energy requirements of the Australian industry; supply chain complexities, high logistics costs and inconsistent waste regulation limit adoption | Nascent technology, basic research or demonstration stages; current costs are prohibitive for widespread adoption | Nascent technologies, some used internationally but not in Australia |

While Australia achieves higher SCM rates in concrete than some markets, such as the US, Global Cement and Concrete Association (GCCA) data indicates that Australian clinker factors are higher than China's and India's due to measurement at the cement rather than the concrete level, and because regulatory frameworks allow the use of large quantities of slag from their iron and steelmaking industry and fly ash from coal-fired power.[136,137]

Further, greater market acceptance by market specifiers, procurers and built environment users of lower carbon cement and concrete is required for increased uptake to occur. This is a key challenge — it is pointless to produce a lower carbon product without introducing incentives and policies to stimulate demand for the product.

Supportive regulatory standards and policies at national, state and local levels will also be required for SCMs to be utilised in cement and concrete (including supportive standards that rely on the performance of the product).

**Energy efficiency** is important to cement manufacturers as energy users, both in the form of electricity and heat. Energy, including thermal energy for the clinker kiln and electricity for the cement grinding plants, represents c.25%-30% of total production costs and c.40% of the industry's GHG emissions.[138]

Historically, coal is the primary fuel used in clinker kilns, but it is also technically possible for kilns to be retrofitted from using coal to using natural gas. Gas produces approximately half the CO2 emissions of coal per GJ of energy,[139] but market pricing following the Liquified Natural Gas (LNG) investment makes natural gas a significantly higher-cost energy source than coal today.

Cement producers are continuously focused on achieving high thermal and electrical efficiency to maintain their competitiveness.[140]

**Alternative fuels, renewable energy and raw materials** can be used as a substitute source of energy and/or raw material for cement and clinker production. Waste materials and by-products of industrial processes can be co-processed as alternative fuels for the kiln. These include municipal waste, agricultural waste and residues, hazardous and non-hazardous industrial and chemical waste, rubber tyres, carbon powders, used oils and solvents, spent cell liners from aluminium production, recycled cement kiln dust, and plastics. Kilns allow for a complete burn-out of waste-derived fuel with rapid combustion, long residence time and complete oxidisation of organic components.

The co-processing of waste in cement kilns increases resource efficiency, reduces demand for virgin raw materials and fossil fuels, and generally lowers CO2 emissions (but not always — hydrocarbon wastes can have high associated carbon emissions). Currently, alternative fuels meet c.18% of the total energy requirements of the Australian cement industry versus the global average of c.16%.[141] The European cement industry substitutes over c.40% of its fossil fuels with waste-derived fuels and biomass, with differences in co-processing rates ranging from 7% to 95%, reflecting variations in subsidies (either indirectly via landfill fees or more directly), local availability, transport costs and technical expertise to utilise alternative fuels.[142] Adbri's Birkenhead plant sources c.25%-40% of kiln fuel from Refuse Derived FuelRDF.[143]

The uptake of alternative fuel is dependent on a range of factors including proximity and access to long-term and reliable sources, transport costs, landfill costs for disposal of waste, capital-intensive infrastructure and regulatory impediments such as consistency of waste regulation across jurisdictions. For example, alternative fuels currently may not be a viable option for clinker kilns located in remote and regional areas requiring high transport and freight costs, and landfill levies would need to rise considerably for there to be improved incentives to increase alternative fuel usage in their operations.

Renewable energy also provides a significant opportunity to address emissions from cement production. While only around 10% of cement production emissions are from electricity, this represents a significant proportion of the emissions from a steady level of cement production that can be addressed without requiring CCUS or offsets (i.e. 55% of total emissions from the production of cement are process emissions and require these approaches). The benefits from increasing the use of renewable energy can be delivered in line with decarbonisation of the grid, and cement grinding is more capable of utilising variable energy than many other industrial processes (subject to sufficient grinding and stockpiling capacities being available).

**Carbon capture, use and storage (CCUS)** is a necessary technology to reduce process emissions related to the chemical transformation of limestone that occurs in the calcination process. While current technology and infrastructure are nascent and highly capital intensive, CCUS is expected to play a role in the long term to deliver net zero emissions.[144] Cement plants are well suited to carbon capture due to the relatively high CO2 concentration in their flue gases relative to other industrial processes (allowing relatively easy purification), few emission points, stable operation and, in some cases, availability of waste heat (which can reduce the energy costs of CCS).[145] However, the Technology Ready Level for CCUS remains low and the process requires significant capital investment and involves higher operating costs.

CCUS presents some significant challenges:

- Carbon capture and storage (CCS) is prohibitively expensive for carbon emitters to pursue individually due to significant capital and direct/indirect operating costs. A specialised pipeline or shipping is required to transport compressed CO2 to storage, with the transportation choice dependent on the location and distance between kilns and storage areas. Pipelines require significant upfront investment but provide lower ongoing costs, while shipping has lower set-up costs but incurs greater storage and delivery costs.[146]

- Carbon capture and use (CCU) has been demonstrated to be viable in some other industries, like ammonia, but demand for CO2 is small (key uses are for oil extraction using enhanced oil recovery techniques and in food and beverage manufacturing) and already met by other industrial processes. Investigations are underway into possible uses for captured carbon dioxide, including as an input for industrial processes requiring carbon or as an input for other building materials, but these uses are generally immature.[143]

**Breakthrough technologies** include alternative binders for clinker substitution, new methods for CCS, and hydrogen fuel.

- Alternative binders like calcined clay (or metakaolin) and carbonated concrete fines can be used directly or as SCM in concrete, or as an ingredient in cement products like lime calcined clay cement (LC3). While Australia has significant deposits of kaolins (clay precursors), the technology is still in its infancy globally and has not been a focus of research for standards and commercial development in Australia.
- New methods for CCS include oxyfuel technology (which would enable a high concentration of CO2 in off gases more efficient capture) and indirect calcination (which would allow for electrification of calcination in the production process). These methods have potential but remain at the prototype stage around the globe.
- Hydrogen fuel (green hydrogen) has potential for partial fossil fuel substitution, and is emissions free when produced through electrolysis using renewable electricity. The technology is still in early stages for commercial application and for cement production in particular (see below).

### b. Delivery of cost-competitive energy

The delivery of cost-competitive, secure and reliable (firm) electricity is a key challenge for the cement sector to resolve in achieving a net zero outcome without operational interruptions.

Cement manufacturing requires a significant amount of electricity to prepare the raw materials, produce clinker and operate grinding mills. In 2018-2019, electrical power consumption from Australian producers was approximately 923GWh. Large amounts of energy in the form of heat are required to raise the kiln temperature to 1,450°C. In 2018-2019, Australian cement producers used 21 petajoules of thermal energy, of which 61% was from coal, 21% from natural gas, 15% from alternative fuels and 3% from diesel. High Australian gas prices linked to Asian LNG prices make it challenging for domestic producers to use gas to reduce carbon emissions and compete against higher carbon imports produced using coal.

Green hydrogen relies on high levels of low-cost renewable energy and can provide some zero-emissions thermal energy for cement production, but it cannot be a complete substitute for all thermal energy requirements, as it cannot meet the heat requirements for clinker formation. Pilot projects have indicated that hydrogen can be used as a source for low carbon thermal energy when paired with other combustibles such as biomass. In February 2020, Hanson Ribblesdale's UK plant piloted the use of hydrogen in the kiln as a partial replacement for natural gas.

The clinker production process needs kilns to operate continuously in order to efficiently maintain high temperatures and high utilisation of expensive capital equipment, making it a very high-fixed-cost process that relies on an uninterrupted (firm) supply of energy.

### c. Rate of global cement industry decarbonation

As described above, cement is a trade-exposed, emissions-intensive industry, and nations are decarbonising at different paces.

Carbon leakage is a particular problem for cement because emissions associated with imported goods are not factored into national emissions inventories. As Australia is an efficient producer of cement with a relatively low emissions intensity, relocating cement manufacturing offshore will most likely result in higher emissions, with additional emissions from shipping included.[147]

In a scenario where there is a loss of domestic competitiveness or complete absence of Australian cement manufacturing, Australian demand could be met through imports from regional markets where there are lower prospects of GHG penalties and less efficient and older-technology kilns, and overall global CO2 emissions will not be reduced.[148] This exposes the supply chain to interruption that can impact construction costs and schedules.

Uneven speeds and approaches for decarbonisation across markets may exacerbate carbon leakage and impact Australia's relative competitiveness. If Australia takes a more aggressive approach to emissions reduction than other markets in our region, a free market will gravitate towards the lowest-cost material unless there is a further incentive or impost (e.g. pricing in the benefit of a lower carbon binder for embodied carbon on a building).

Australian emissions policy needs to ensure that it does not create incentives to offshore emissions.

### d. Standards and market acceptance for cementitious products

Cement must meet rigorous standards to ensure that concrete used in the construction of long-lived assets performs as expected.

There are different types of cements and concretes permitted under regulatory standards (for example, AS3972-2010, defining general-purpose and blended cements), permitted in accordance with asset standards of infrastructure owners like airports or road agencies, produced by the Australian cement and concrete industry, and adopted in accordance with established engineering practices of asset owners.

These cements and concretes can have different levels of embodied carbon depending on the amount of clinker that is used to create the binder for the concrete (that is, the clinker-to-concrete ratio).

The relationships between standards, production and distribution infrastructure, and market demand are complex. Misalignments amongst these different elements can have a range of negative consequences ranging from increased emissions associated with reduced use of SCMs in either cement or concrete through to increased costs for customers and producers, or poor asset performance impacting safety and longevity of infrastructure.

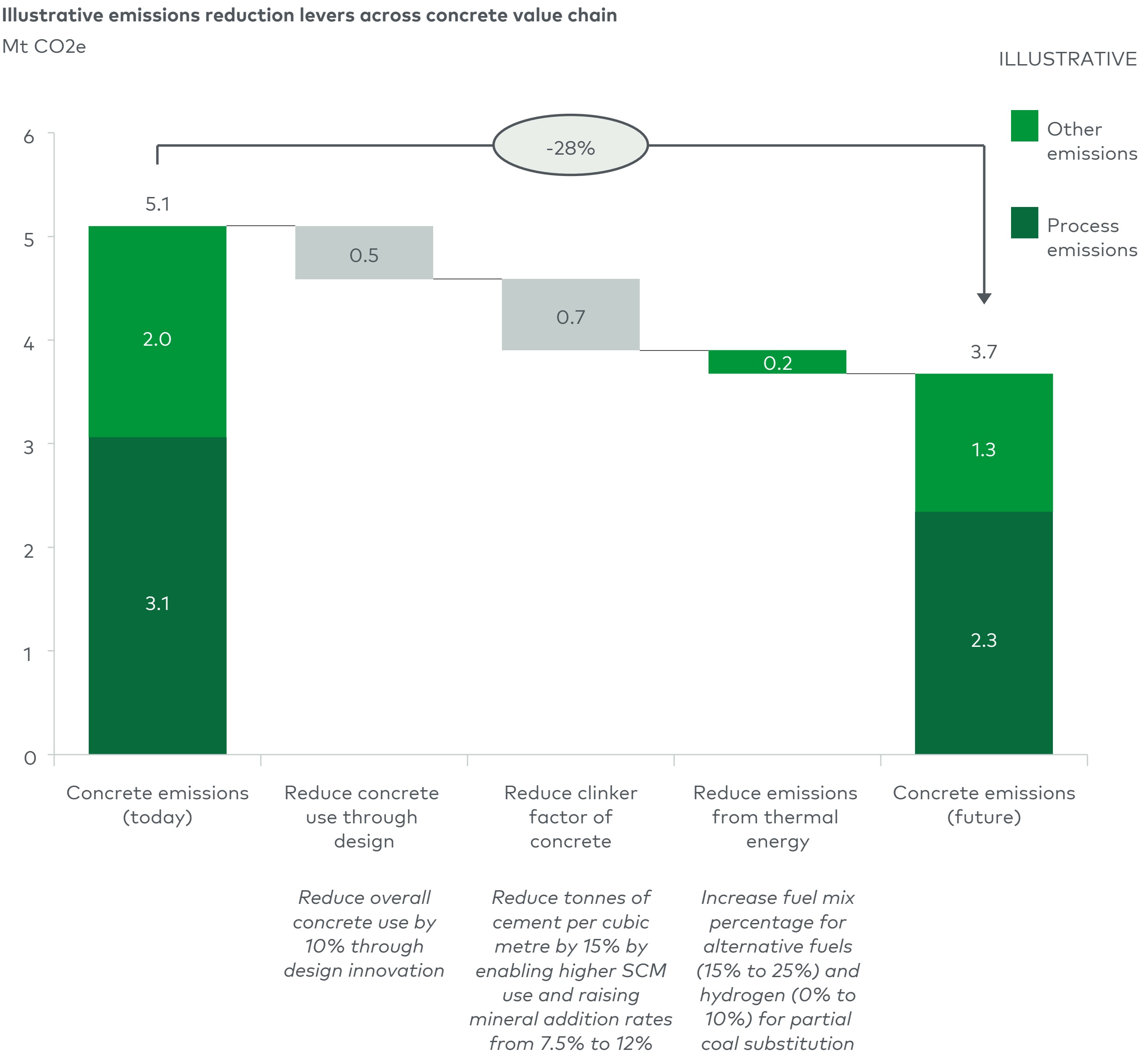
There are many different approaches that can reduce the clinker-to-concrete ratio that ultimately drives reduced emissions from use of concrete, and it is important not to narrowly focus on emissions associated with a single part of the cement and concrete value chain, especially when comparing across countries. High levels of SCMs in ready-mix concrete production in Australia can deliver low clinker-to-concrete ratios, as can blending SCMs into cement during European production, but it is not simple (or necessary) to change from one model to another to achieve the desired outcome of reduced overall emissions.

Overall, there is a worthwhile prize for Australia to adopt collaborative approaches to evolve standards, develop products and provide leadership from key customers like road agencies and other major infrastructure owners. With all parties being open to change, it is possible for Australia to deliver material emissions reductions from cement and concrete use without necessarily imposing significant costs.

## 4.4 Cement pathways to net zero

Cement is commonly considered to be one of the most difficult sectors to abate due to its significant process emissions that result simply from its production. There are limited opportunities to reduce scope 1 and scope 2 emissions at the cement kiln, apart from sourcing green electricity and increased usage of alternative fuels. In the longer term, CCU and CCS are likely to become extremely important (particularly after 2030 and 2040). As a result, the federal government's Safeguard Mechanism will provide little incentive to reduce emissions if facility baselines are reduced and Australian manufacturers are exposed to imported product that does not face similar emissions constraints, with carbon leakage the likely result.

**Figure 34**
Emissions reduction levers across concrete value chain



Source: National Greenhouse Accounts Factors, 2020; CIF; L.E.K. analysis

However, if the challenge/opportunity is framed as lowering the embodied carbon in concrete, significant emissions reductions are possible when considering the full cement and concrete value chain. For example, a c.30% reduction in emissions could be achieved from three steps that do not require any capture of process emissions nor exhaust all thermal emissions reduction potential.

The illustrative emissions reductions chart above demonstrates how emissions reduction for cement and concrete will require multiple simultaneous approaches — there is no 'silver bullet' that can be relied upon, and collaboration amongst asset owners, designers, standards bodies and industry will be required.

## Case study: Existing emissions reduction efforts in the Australian cement industry

### Cement Australia energy from waste

Cement Australia has embraced the use of high viscosity fuels (HVF) and solvent based fuels (SBF) as supplementary materials to provide thermal energy to its cement kilns at Railton in Tasmania and Gladstone in Queensland.

Geocycle, a wholly owned subsidiary company of Cement Australia, operates a licensed waste management facility that blends and transforms a wide range of industrial and prescribed industrial waste streams at their Dandenong Victoria facility into an alternative fuel.

This fuel is then transported to the Railton and Gladstone facilities and introduced to the kilns in conjunction with other fuel sources for the manufacture of clinker.

Wastes with a range of energy values are blended into alternative fuels. These wastes can include flammable, hazardous and otherwise difficult waste streams with limited suitable disposal options, such as spent solvents, waste fuels, paints, resins, oils and greases, waste waters, fertilisers, and agricultural chemicals.

In addition to these materials, some industrial wastes are received directly by Cement Australia for use as alternative fuels. These waste materials include spent cell liners, a waste material generated in the aluminium smelting industry, and spent catalysts from the oil refining industry.

Both of these waste materials also still maintain a calorific value useful to the process.

Since 2009, the use of alternative fuels in the cement kilns by Cement Australia has:

- Delivered over 8,800,000 Gigajoules (GJ) of energy from waste
- Avoided the consumption of over 362,000 tonnes of coal
- Reduced greenhouse gas emissions by approximately 117,000 tonnes CO2-equivalent
- Diverted approximately 128,000 tonnes of solid and 147,000 tonnes of hazardous liquid waste from landfill

Cement Australia continues to focus on the increased use of alternative fuels and optimising the opportunities in the area of energy from waste. Australian cement kilns can play a vital role in waste recovery strategies as a major consumer of waste and by-products from other industries.

### Adbri refuse-derived fuel

As the first company in Australia to take on the burning of refuse-derived fuels (RDF), Adbri's initial challenge at its Birkenhead plant was to reengineer its kiln firing system to allow for the burning of RDF.

(Continued)

Adbri collaborated with a local resource recovery supplier and developed an effective process for the recovery and refining of combustible material from the mixed construction and demolition refuse stream.

A three-year development phase saw both partners working together to establish a significant supply of viable fuel.

Adbri faced and overcame the challenges of receiving, storing, and consistently monitoring and feeding the RDF to the cement kiln at Birkenhead. All this had to be achieved while maintaining steady operations, producing quality cement, and meeting regulated site environmental and work health and safety standards.

Adbri worked collaboratively with the SA Environmental Protection Authority, the Adbri Community Liaison Group and the local community to develop a site environmental licence to manage the use of RDF. Throughout the project life cycle, the community was kept informed of progress — including monitoring and reporting air quality conditions related to the combustion of RDF.

As an added benefit, emissions analysis shows a significant reduction of airborne nitrous oxide emissions when RDFs are used, and the residual ash is entirely encapsulated in the kiln product to become saleable cement.

Adbri's RDF programme has resulted in a South Australian construction and demolition refuse product (that would otherwise be destined for landfill) being given a second life as an alternative, supplemental fuel source.

In one year, the Adbri RDF programme saves the combustion of 1.2 million gigajoules (GJ) of natural gas and diverts approximately 200,000 tonnes per annum of material away from landfill. Approximately half is used as a fuel source. The balance is separated through the sorting process and used in other useful inorganic products such as metals, sands and aggregates.

Through the incorporation of refuse-derived fuels, a stronger and more sustainable construction and cement manufacturing sector has been built, which compares favourably with international benchmarks and is at the forefront of Australian industry best practice.

## 4.5 Australia's future competitiveness with low emissions cement

High-level analysis suggests that clinker production costs would increase substantially when pursuing key emissions reduction approaches, demonstrating the importance of dealing with scope 3 emissions as an emissions-intensive trade-exposed (EITE) commodity. Gas, alternative fuels and green hydrogen can lead to significant emissions reduction, but they are prohibitively expensive for cement manufacturers to pursue at current costs and targeted prices.

It is important to note that decarbonising cement is more than addressing traditional fossil energy sources, as process emissions account for over 55% of the cement emissions profile.

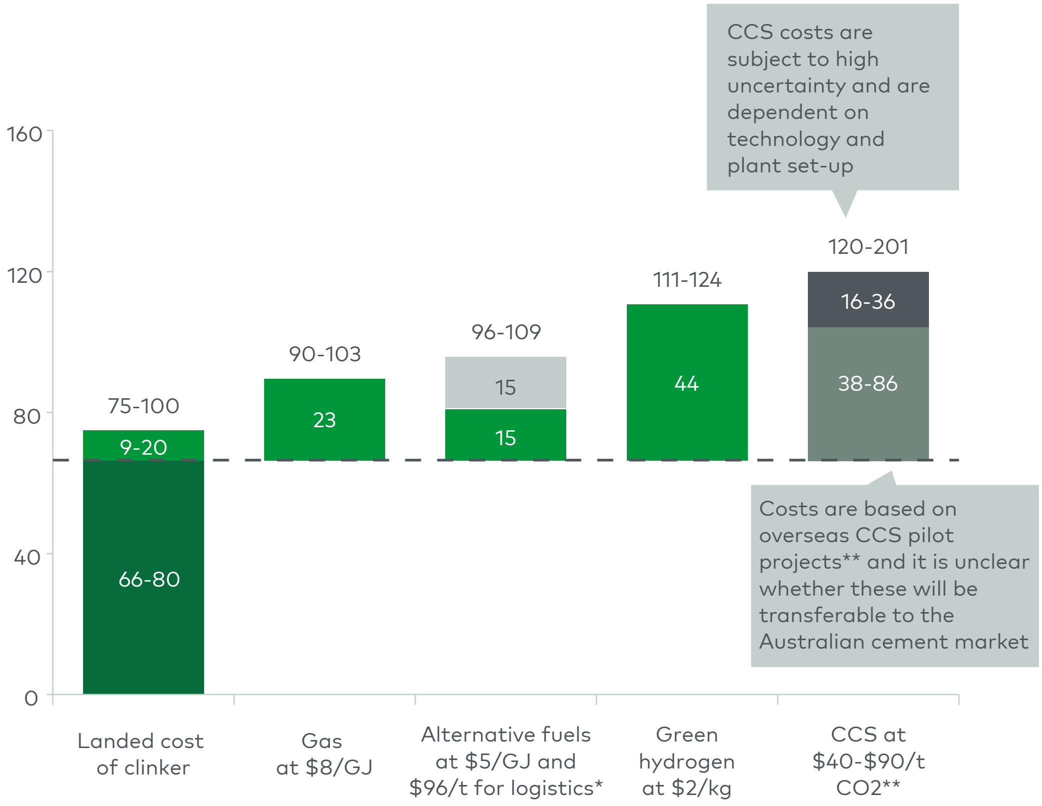
However, over the longer term, Australia should have several natural competitive advantages in a decarbonised world that aligns it to being a competitive player in the global cement market, namely:

- A combination of solar and wind resources that should be able to provide Australia with an energy cost advantage

**Figure 35**
Cost impact of selected emissions reduction approaches

**Cost impact of selected emissions reductions approaches**
Dollars per tonne of clinker

PRELIMINARY



CCS costs are subject to high uncertainty and are dependent on technology and plant set-up

Costs are based on overseas CCS pilot projects** and it is unclear whether these will be transferable to the Australian cement market

| Landed cost of clinker | Gas at $8/GJ | Alternative fuels at $5/GJ and $96/t for logistics* | Green hydrogen at $2/kg | CCS at $40-$90/t CO2** | |
|---|---|---|---|---|---|
| 12%-20% | 31%-35% | 19%-26% | 56%-59% | N/A | Energy costs as percentage of landed cost of clinker |
| N/A | 0.11 | 0.20 | 0.26 | 0.53-0.74** | Emissions reduction vs coal (t CO2e/t of clinker) |

*Logistics costs of $96/tonne of biomass for transporting biomass in an articulated truck for 500km; **Costs and emissions reductions based on overseas CCS pilot projects for post-combustion and direct capture CCS methods at Capitol Aggregates (Texas, US), Norcem (Brevik, Norway), Lafarge (British Columbia, Canada) and Heidelberg Cement (Lixhe, Belgium) Analysis as of July 2021

Source: CSIRO, UK Department of Business, Energy & Industrial Strategy; MDPI Energies Journal; Global CCS Institute; Pearman, G. 'Overheads of truck transport in Australia: implications for biomass as feedstock for bio-energy' (2018); L.E.K. analysis if they can be combined with competitive sources of clean, 'firm' electricity — with this firm electricity being a fundamental issue yet to be resolved

- Space available to scale and create renewable energy assets with a resulting cost advantage
- Opportunities to leverage trust and strong regulatory frameworks to enable opportunities to reduce embodied carbon in concrete, but with a need to understand regulatory interdependencies that limit delivery of this goal and to make changes to better utilise waste products as alternative fuels in cement kilns and industrial by-products (e.g. blast furnace slag from domestic steel production, new and old fly ash from electricity generation, spent cell liners from alumina processing) as SCMs.

The cement manufacturing sector in Australia is dependent on a number of other stakeholders to ensure that it can remain competitive, profitable and vibrant within an Australian context. The key enablers of Australian cement manufacturing competitiveness in a transition to net zero are:

- Continuing to recognise cement as an emissions-intensive trade-exposed product and proactively addressing risks of carbon leakage
- Addressing carbon accounting issues for imported cement and considering emissions across the whole of the concrete value chain
- Implementing a consistent and integrated approach to climate and energy policy to provide certainty and stability in the Australian electricity market
- Demonstrating leadership throughout government to develop and adopt cement and concrete with lower embodied carbon, including through infrastructure project procurement requirements, devoting resources to trials, supporting increases in the allowable level of mineral addition, and adopting a performance-based approach to cement and concrete standards
- Facilitating or otherwise streamlining access to grants and other funding from federal and state governments to implement emissions reductions
- Accounting for carbon recarbonation on a life-cycle basis to give incentives for designing structures and infrastructure to maximise this effect to store carbon
- Streamlining waste policy and resetting landfill charges to be consistent across state governments to incentivise the processing of waste in cement
- Developing innovation and R&D policy that promote investment in cement technology

# About Manufacturing Australia

Manufacturing Australia (MA) is a CEO-led coalition of Australia's largest manufacturers. MA works with governments to help Australia's manufacturing sector realise its potential. MA proposes and supports practical policy measures to ensure that Australian manufacturing remains internationally competitive.

MA does not support protectionism and believes that manufacturers should be wholly accountable for their own performance. Having overcome a myriad of external economic challenges in recent years, MA members continue to operate at scale because they are efficient, well-managed and innovative businesses that have restructured and retooled to improve productivity and remain competitive.

Manufacturing is the value-adding lifeblood of a balanced Australian economy. Through downstream wealth creation, research and development, import replacement, and maximising the value of our natural resources, manufacturing delivers a substantial economic, social and cultural return to the nation.

Almost one million Australians work in manufacturing. Competitive manufacturing brings with it skilled direct and indirect employment, innovation, and thriving local communities.

**Manufacturing Australia's priorities**

Manufacturing Australia works to secure the next generation of manufacturing employment and investment in Australia by focusing on four priority areas for cooperation between industry and government. These are:

- Encouraging better regulations that help keep Australian manufacturing safe, sustainable, productive and high quality
- Increasing productivity through innovation, research and development, and modern and flexible workplaces
- Ensuring that free trade is also fair trade
- Regaining Australia's competitive advantage of reliable, affordable and sustainable energy resources, and ensuring that Australia meets its international emissions obligations while remaining globally competitive in trade-exposed industries

Manufacturing Australia's members include:

- Adbri
- Alumina
- BlueScope
- Brickworks
- Capral
- Cement Australia
- CSR
- DuluxGroup
- Incitec Pivot
- Orora
- Rheem
- Tomago Aluminium

# About L.E.K. Consulting

L.E.K. Consulting is a global management consulting firm that uses deep industry expertise and rigorous analysis to help business leaders achieve practical results with real impact.

We are uncompromising in our approach to helping clients consistently make better decisions, deliver improved business performance and create greater shareholder returns.

The firm advises and supports global companies that are leaders in their industries — including the largest private- and public-sector organisations, private equity firms, and emerging entrepreneurial businesses.

With offices in the Americas, Asia-Pacific and Europe, we have an established presence in key business centres worldwide.

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# Appendix

| Abbreviations and acronyms | Definitions |
|---|---|
| **BF** | Blast furnace |
| **BOF** | Basic oxygen furnace |
| **CAPEX** | Capital expenditure |
| **CCS** | Carbon capture and storage |
| **CCUS** | Carbon capture, usage and storage |
| **CO2** | Carbon dioxide |
| **CO2e** | Carbon dioxide equivalent |
| **DRI** | Direct reduced iron |
| **EAF** | Electric arc furnace |
| **GDP** | Gross domestic product |
| **GHG** | Greenhouse gas |
| $H_2$ | Hydrogen |
| **IEA** | International Energy Agency |
| **LME** | London Metals Exchange |
| **NEM** | National Electricity Market |
| **OPEX** | Operating expenditure |

| Units of measure | Definitions |
|---|---|
| **J** | Joule |
| **t** | Metric tonne(s) (1,000kg) |
| **W** | Watt |
| **Wh** | Watt-hour |

The following prefixes have been used with W, Wh, J and t (watt, watt-hour, joule and tonne) to denote larger quantities.

| Prefix symbol | Prefix | Quantity |
|---|---|---|
| **K** | kilo- | $10^3$ |
| **M** | mega- | $10^6$ |
| **G** | giga- | $10^9$ |
| **P** | peta- | $10^{15}$ |

## Endnotes

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