A New Chapter

Opportunities to seed new industries for Queensland over the coming decade

Citation

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Important disclaimer

Currency conversions

All dollar value figures denote Australian dollars unless otherwise specified. Conversions were made using the annual average exchange rate for a given currency, as specified by the Reserve Bank of Australia's historical data. Conversions for forecast values were made using the June exchange rate for the year in which the forecast was calculated.

Contents

Figures

Tables

Executive summary

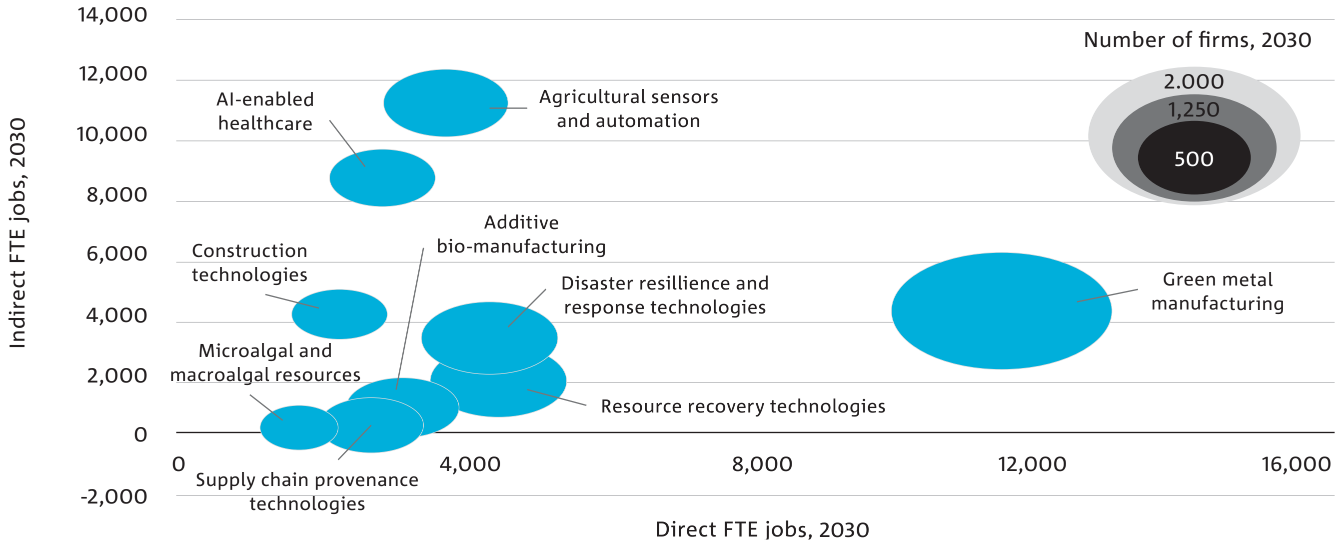
Queensland's post-COVID economic recovery and transformation depends on being ready for new economic opportunities. In a time of significant change and disruption, the state has an opportunity to harness its strengths in science and technology to position itself ahead of the curve. This report was developed by CSIRO and the Queensland University of Technology's Centre for Future Enterprise and commissioned by the Queensland Department of Environment and Science. It aims to explore the areas where Queensland's scientific and technological capabilities overlap with its comparative advantages and state priorities, opening up the potential to seed new industry opportunities for the state.

Through this work, a set of nine emerging, knowledge-driven seed industries have been identified as having potential for strong, sustained jobs growth, if supportive ecosystems can be established for them. They should not necessarily be viewed as the only opportunities or the best opportunities for Queensland, but as additional options for policy-makers to consider. Each of the nine seed industries presented in this report is defined using a holistic approach that considers the social, economic and environmental benefits and costs, to support innovation and entrepreneurship, investment and job creation opportunities and overall economic outputs and exports for Queensland.

Emerging knowledge-driven seed industries for Queensland out to 2030

The emerging seed industries reflect example strategic areas where Queensland has an advantage in successfully creating new knowledge-driven industry development opportunities for the state, acknowledging that opportunities might exist in other areas too. Each seed industry was defined by the convergence of supporting supply and demand drivers and quantified using an innovative data-driven approach that estimated the potential the number of firms in each emerging sector. The potential job creation opportunities associated with these seed industries were also quantified in terms of the number of full-time equivalent (FTE) jobs directly employed in the seed industry ('direct FTE jobs') and indirectly employed in industries that form part of the seed industry's value chain ('indirect FTE jobs').

EMERGING KNOWLEDGE-DRIVEN SEED INDUSTRY	DESCRIPTION
Additive biomanufacturing	Using additive manufacturing processes for medical applications to provide highly customised body parts, scaffolds or medical devices
AI-enabled healthcare	Leveraging growing capabilities in artificial intelligence (AI) and electronic medical records to improve health outcomes and system efficiencies
Green metal manufacturing	Creating new value in the manufacturing and mining sectors by taking advantage of the state's abundant clean energy and mineral resources
Resource recovery technologies	Transforming existing waste streams into higher-value products, diverting waste from landfill, and reducing demand on virgin materials
Microalgal and macroalgal resources	Contributing to solving significant global food, water, and emissions challenges by using natural resources and local expertise to grow algae
Agricultural sensors and automation	Applying robotics, sensors, and other automation technologies to boost the productivity and global competitiveness of the agriculture sector
Supply chain provenance technologies	Building trust and increasing the value of exports by using technologies to improve the traceability, transparency and authenticity of supply chains
Disaster resilience and response technologies	Translating existing capabilities in robotics, autonomous systems and data analytics to improve preparedness and resilience to disasters
Construction technologies	Reducing safety risks in the construction sector by using assistive technologies and maximising off-site automated processing



Number of direct and indirect full-time equivalent (FTE) jobs and firms by 2030 for each knowledge-driven seed industry.

Future policy directions for knowledge-intensive industry development

Each of the nine emerging knowledge-driven seed industries will have unique challenges in establishing new economic growth and job creation pathways in areas such as regulation, public policy, access to skilled workers and the cost of enabling technologies. While the challenges might be industry-specific, some common themes emerged across this cluster of potential seed opportunities:

- There is a need to develop strong business ecosystems that consist of mature, established firms, innovative start-ups and cutting-edge researchers, and take advantage of Queensland's comparative strengths in attracting larger international firms that are established players in these industries.
- Job creation opportunities exist in the transferability of skilled workers from existing industries in Queensland, particularly those industries at risk of future decline. The future workforce of knowledge-driven industries will depend upon the right education, training, social support and upskilling pathways to support workers in translating their capabilities, as well as creating a healthy pipeline of new talent and graduates.
- Advanced manufacturing is at the core of many emerging knowledge-driven seed industries. Combining Queensland's manufacturing capabilities with its other strengths (e.g. geographical, workforce, research resources and capabilities, etc.) could give the state a competitive edge in these industries, both domestically and globally.
- The domestic markets for some of these sectors are small. Government could play a role in seeding initial domestic demand for these industries and supporting them to scale into export markets, which could open up larger market opportunities.
- There is a need for contemporary and adaptive regulatory systems. Government could achieve this by working with industry and academia to find the right balance between mitigating potential future risks and encouraging future growth and innovation.
- There are flow-on benefits from the identified knowledge-driven industries for other emerging and established sectors. Growth in these seed industries could bolster activities in the firms that form part of each industry's value chain (i.e. through increased demand) or stimulate research and development activities and capabilities that can be applied in other industrial sectors.

For any of the nine knowledge-driven seed industries presented in this report, strong leadership, strategic direction and collaboration across government, industry and academia will be needed to drive the opportunities forward. Instead of relying on incremental changes, these industries present opportunities to seed new sources of economic growth and job creation for Queensland, driven by cutting-edge science, technology and innovation. The COVID-19 pandemic has caused significant disruption to the Queensland economy and abroad, but with this disruption comes an opportunity to set a new strategic direction for the state towards a 'new normal' for economic development that has knowledge at its core.

Introduction

Queensland has a strong track record in innovation and entrepreneurship, and initiatives such as the Smart State Strategy and the current Advance Queensland initiative have supported the state in identifying new sources of economic growth and job creation. The foundations of Queensland's economy have been underpinned by its existing strengths in sectors linked to natural resources, like mining, tourism, and agriculture, as well as construction, health and education. The state is also institutionally and geostrategically positioned to capitalise on innovative seed industries connected to these and other areas of comparative advantage.

Advances in enabling technologies, combined with existing research capabilities, local, national and international market shifts and the emergence of new markets, present opportunities for Queensland to seed new industries and increase the knowledge-intensification of existing or previously dormant industries. By using the existing foundational strengths within the state's innovation ecosystem, Queensland has the opportunity to leverage its comparative advantages to significantly accelerate the growth of key seed sectors and drive new sources of job creation and economic prosperity, improve quality of life for all Queenslanders and support the state in transitioning to a zero-carbon economy.

In 2019, in collaboration with the Queensland Department of Environment and Science, CSIRO's Data61 published the *New Smarts* report, which identified eight knowledge-intensive industries that are currently emerging across Queensland.[1] This report began to draw the links between Queensland's comparative advantages in science and research and broader shifts in supply and demand, emerging technologies and local, national and global markets. Using the original *New Smarts* knowledge-intensive sectors as a starting point, this report aimed to provide a more nuanced view of Queensland's knowledge-intensive economic development opportunities and identify a set of specific seed industries that form part of these broader emerging industry areas.

This work was conducted by CSIRO and the Queensland University of Technology's (QUT) Centre for Future Enterprise and commissioned by the Queensland Department of Environment and Science. Each of these nine knowledge-driven seed industries present feasible, scalable and novel opportunities for Queensland to leverage existing, but currently underutilised, innovation and knowledge. As Queensland recovers from the impacts of the global COVID-19 pandemic, these sectors could present opportunities to transition the state into a 'new normal' and thrive in the face of significant disruption and adversity. Importantly, the seed industries explored in this report should not be viewed as the only opportunities or the best opportunities, but as additional options for consideration by Queensland policy-makers.

Many of these industries reflect sub-sectors to the original *New Smarts* emerging knowledge-intensive sectors. For example, additive biomanufacturing and AI-enabled healthcare could be considered as part of the previously defined 'personalised and preventative healthcare' industry, which uses technologies such as AI, robotics, sensors and 3D printing to customise healthcare services and improve system efficiency and efficacy and patient outcomes. Other sub-sectors were identified across the previously defined 'sustainable energy' and 'advanced materials and precision engineering' industries (i.e. green metal manufacturing); 'circular commodities' (i.e. resource recovery technologies) and 'advanced agriculture' (i.e. microalgal and macroalgal resources, agricultural sensors and automation and supply chain provenance technologies). However, the present analysis also uncovered additional opportunity areas that extend beyond the original *New Smarts* industries (i.e. disaster resilience and response technologies and construction technologies). These industries present new opportunities to draw upon Queensland's research and science strengths in response to growing local and global market demands.

The nine emerging knowledge-driven seed industries presented in this report are:

- additive biomanufacturing
- artificial intelligence (AI) enabled healthcare
- green metal manufacturing
- resource recovery technologies
- microalgal and macroalgal resources
- agricultural sensors and automation
- supply chain provenance technologies
- disaster resilience and response technologies
- construction technologies.

Notably, these knowledge-driven seed industries are not isolated opportunities. Queensland's traditional industry base in areas such as mining, manufacturing, agriculture and construction provides the core foundations for many emerging industries. The report highlights the intersection between these emerging opportunities, and how these industries could support existing resources, industries and capabilities. For example, Queensland's strong agriculture sector is a key enabler of various seed industries, such as agricultural sensors and automation and supply chain provenance technologies. Similarly, the state's comparative advantage in green metal manufacturing stems from Queensland's existing skilled workforce from the mining and manufacturing sectors. As such, the emerging knowledge-driven seed industries discussed in this report will likely be enabled by, and an enabler of, the future growth of Queensland's traditional industries.

The research presented in this report adopts a pragmatic mixed-method approach, combining qualitative data, insights from key experts and desktop research to characterise each knowledge-driven seed industry with an innovative data-driven analysis to estimate the potential size of each sector by 2030. Each industry opportunity is defined by a series of supply and demand drivers, which provide signals to the future feasibility and scalability of the industry over the coming decade. The size of each seed industry in 2019 and 2030 is quantified by the number of firms and full-time equivalent (FTE) jobs in that seed industry, including persons that are employed directly and indirectly (i.e. persons employed in industries that are part of the seed industry value chain).

Projected industry growth is juxtaposed with published projections of global growth in comparable industries and technologies. For example, a higher local growth rate may signify a revealed comparative advantage, whilst a lower local growth rate may signify a barrier in the local industry ecosystem. However, local growth rates may vary from global rates for a variety of reasons which are beyond the scope of this report. Additionally, the estimates and forecasts for each industry are largely based on historical figures up until 2019, and as such, they do not take into account the impacts of the COVID-19 pandemic. More recent events are, however, considered in the exploration of supply and demand trends and drivers for each industry. There is also a high degree of uncertainty associated with projecting the potential size of future industry opportunities given these industries are yet to formally emerge. As such, the seed industries presented in this report may take more or less than 10 years to reach their commercial potential, and this timeframe will depend on a range of factors, including the level of strategic investment in the industry from the public and private sectors. Please refer to *Appendix: Project Methodology* for further details.

This work aims to provide evidence-based insights to inform future strategic decisions around investment, industry attraction, diversification and resilience strategies for Queensland, particularly in a post-COVID-19 era. Many industries have undergone significant disruption, and in some cases, accelerated market shifts and digital transformation, and the time is right for exploring new industry development opportunities for Queensland. In doing so, this report not only identifies how these emerging knowledge-intensive industries will develop but also how these new industries will be engines of economic development, fostering the creation of new jobs, growing local economies, attracting foreign investment and opening up new avenues for future exports.

1 Additive biomanufacturing

Additive biomanufacturing is an emerging field that falls at the intersection of engineering, design, computer science and medical science. Here additive manufacturing approaches (also known as 3D printing) are used to design, develop, and manufacture highly customised body parts, scaffolds, replacement bone, organs or tissue or medical devices. Research into this opportunity explores the development of the technology and hardware (e.g. 3D multi-material and multi-functional bioprinters), the biomaterials used for additive biomanufacturing (i.e. 'bioinks'), 3D scanning and modelling of the human body, its cells, tissues and organs, and the design and development of innovative clinical applications. Additive biomanufacturing is also being used to develop personalised and customised surgical instruments that clinicians can use to treat a range of health conditions or injuries.

There is strong strategic alignment between additive biomanufacturing and other supporting sectors like advanced manufacturing and biomedical and life sciences, which have been the focus of several industry development roadmaps for the Queensland Government.[2,3] Moreover, Queensland has a rich network of research groups and facilities across its university and hospital sectors with deep expertise in additive biomanufacturing, biofabrication, medical technologies and biotechnology, which provide the knowledge base needed to grow and develop this industry. A cluster of global and local medical technology companies is already emerging in South-East Queensland, some of which are using additive manufacturing for biomedical applications. This cluster could be leveraged to grow Queensland's reputation in this space. Medical technologies and advanced manufacturing are also prioritised in federal and state government investment, providing opportunities to attract new additive biomanufacturing firms and capabilities to Queensland and support the growth of existing ones.

2019	2030
134 businesses	**636** businesses
637 direct FTE jobs **203** indirect FTE jobs	**3,024** direct FTE jobs **963** indirect FTE jobs

There were 134 additive biomanufacturing businesses in Queensland as at 30 June 2019 and this is projected to increase to 636 by 2030 (see Figure 1). These reflect firms that directly form part of the additive biomanufacturing industry, acknowledging that there will be other firms that are associated with this industry's value chain. These businesses are estimated to account for 637 direct FTE jobs and 203 indirect FTE jobs in Queensland currently and this is predicted to increase to 3,024 direct and 963 indirect FTE jobs by 2030 (see Figure 1). These projections are based on an adjusted 10-year average annual growth rate of 15.2%. To illustrate the potential growth of this sector based on current global growth rates, the number of firms and jobs were also forecast using published global growth estimates from a comparable or related sector. For additive biomanufacturing, the additive manufacturing and materials market, which is predicted to grow by 27.5% between 2020 and 2025,[4] was used as an estimate of global growth rates. As shown in Figure 1, the projected growth of this industry based on global estimates could be even more accelerated if an equivalent rate of change was observed in Queensland.

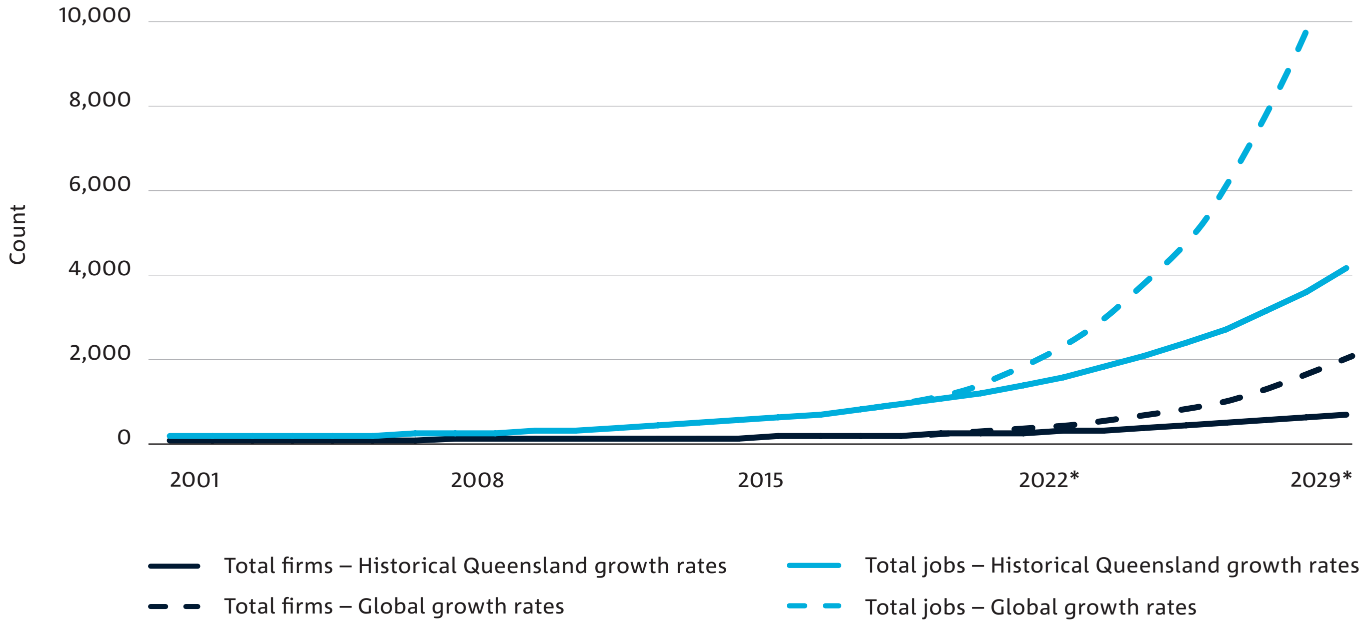


Figure 1. Historical and projected (based on historical Queensland growth rate and global growth rate) number of GST-registered firms and total full-time equivalent jobs (including direct and indirect jobs) in the additive biomanufacturing industry in Queensland

Note. Years denoted by an asterisk (*) reflect forecasted years.

Why Queensland?

QUEENSLAND'S POTENTIAL ADDITIVE BIOMANUFACTURING INDUSTRY AT A GLANCE	
Demand drivers	• Rising demand for healthcare services and innovations, driven by an ageing population and rising rates of morbidity • A growing global precision-medicine market, fuelled by consumer demand for personalised products and services
Supply drivers	• Significant federal and state government investment in advanced manufacturing and biomedical sciences • A thriving network of government, industry, hospital and university partners, including the Herston Biofabrication Institute and the Queensland node of MTPConnect • Advanced research capabilities in additive manufacturing for biomedical purposes and other applications across UQ, QUT and Griffith University • An existing cluster of medical technology firms in South-East Queensland, including Field Orthopaedics, iOrthotics, 61medical and Oventus Medical
Challenges and future opportunities	• The need to engage all stakeholders in developing new regulatory processes to ensure they are fit-for-purpose and keep pace with technological developments • Opportunities to leverage Queensland universities' access to 3D printers and other hardware needed to develop new prototypes and products • Strong competition domestically in Australia in biomedical research and the need for strong leadership and a clear vision and strategy for the industry

Demand drivers

Ageing population, longer lifespans and rising morbidity. Queensland's population is ageing at an accelerated rate, with the number of persons aged 65 years or over projected to increase faster than the rest of the population (see Figure 2). This trend is observable at the national and international level too, particularly in Asian countries. For example, in 2017, 27.1% of Japan's population was aged 65 years or over (versus 15.0% in Queensland) and this is expected to increase to 30.9% by 2030 (17.8% in Queensland).[5,6] Improvements in modern medicine mean that people are also living longer, with the average life expectancy for Australian males being 80.[7] years and 84.9 years for females (2016–18 figures) – up 4.8 years for males and 3.4 years for females over the past 20 years.7 Health risk factors, like rising rates of overweight and obese persons,[8,9] unhealthy diets[10] and physical inactivity[10] are having a negative impact on health outcomes and placing increased strain on the healthcare system. As people live longer and as rates of morbidity rise, demand for healthcare services and innovations are likely to increase too.

Increasing consumer demand for personalised products and services. There is evidence of personalisation of products and services across a range of industries, including banking, retail, hospitality, education, transport and increasingly healthcare. Precision-medicine approaches provide opportunities to tailor medical treatments to a patient's unique biological or genetic characteristics,[11] potentially reducing negative side effects of treatment and improving survival and response rate.[12] Additive manufacturing reflects an emerging area of precision medicine, providing opportunities to develop personalised pre-surgical and surgical tools, implants, synthetic organs, and drugs customised to a patient's needs and condition.[13] Precision medicine has been enabled by advances in key technologies, such as genome sequencing, AI, and enhanced computing power and connectivity.[12] The declining cost of 3D printing is also favouring additive manufacturing over traditional methods, including its use for biomedical applications.[14] The global precision healthcare market is set to grow substantially in coming years, with the market value expected to increase from $57 billion in 2019 to $119 billion by 2026.[15] North America currently makes up the leading share (40%) of this market, followed by the Asia Pacific region (21%).[15]

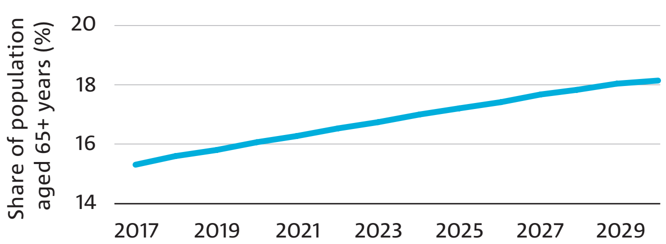


Figure 2. Projected share of the total population aged 65 years or over in Queensland (base year = 2017)

Data source: Australian Bureau of Statistics[6]

Supply drivers

Government investment in advanced manufacturing and biomedical sciences. Advanced manufacturing has attracted significant public investment in Australia, with the Australian Government allocating $100 million to the Advanced Manufacturing Fund in 2017–18, which aimed to support advanced manufacturing innovation, research, development and training opportunities for manufacturing businesses.[16] The Queensland Government has also committed $50 million to support local manufacturing of medical supplies as part of the state's strategy to recover from COVID-19.[17] For biomedical sciences, the Australian Government invested $5 million in the 10-year Medical Research Future Fund in 2015 to support a broad range of health and medical research, innovation and translation activities.[18] The return on this investment in medical technologies is already apparent, with up to $20 million in savings from the health budget due to be reinvested in this fund by 2020–21.18 The Australian Government has also invested $250 million as part of the $501 million Biomedical Translation Fund to develop and commercialise biomedical discoveries, with the remaining $251 sourced from private-sector capital.[19] These and other funding pools could be leveraged by researchers and companies working in additive biomanufacturing to develop this opportunity in Queensland.

A network of government, industry, hospital and university partners. Queensland has access to high-calibre hospitals, a highly skilled healthcare workforce and a strong culture of collaboration between Queensland hospitals and universities. Example collaborations include the Herston Biofabrication Institute – Australia's first biofabrication institute – which is a multidisciplinary partnership between The University of Queensland (UQ) and the Metro North Hospital and Health Service that specialises in 3D scanning, modelling and printing of medical devices, bone, cartilage and human tissue.[20] Queensland hospitals are also actively driving Queensland's research into additive biomanufacturing and biofabrication. The Prince Charles Hospital's Queensland Cardio-Respiratory Biofabrication Centre, for example, researches biomaterials and biomedical engineering applications for critically ill patients.[21] MTPConnect, the national growth centre for the medical technology, biotechnology and pharmaceutical sector, has a node in Queensland, located at the Translational Research Institute.[22] This node provides training and manufacturing facilities to translate early-stage clinical discoveries and products into clinical human trials.[22]

Strong research capabilities in additive biomanufacturing. QUT's capabilities in additive biomanufacturing are housed within the Institute of Health and Biomedical Innovation and the Australian Research Council (ARC) Industrial Transformation Training Centre in Additive Biomanufacturing. These centres develop advanced bioprinters and bioinks, and use additive manufacturing to develop customised and personalised biomedical applications.[23] Researchers at UQ's Australian Institute for Bioengineering and Nanotechnology also work in a range of bioengineering and advanced biomanufacturing fields.[24] Griffith University has established the Advanced Design and Prototyping Technologies Institute, which applies 3D digital scanning and 3D functional modelling and prototyping for biomedical and other industrial applications.[25] The establishment of this facility was a critical aspect in attracting global 3D-printing technology company, Materialise, to relocate its Australian headquarters from Sydney to the Gold Coast.[26] Griffith University also specialises in modelling and simulating personalised 'digital twins' to explore the functioning of human cells, tissues and organs, and uses additive manufacturing to print therapeutic devices and bioengineered scaffolds to repair tissues.[27]

South-East Queensland cluster of medical technology firms. Queensland is home to a number of medical technology companies. Field Orthopaedics designs, develops and manufactures surgical tools for orthopaedic practice.[28] iOrthotics uses 3D printing and advanced design software to produce custom orthotics that are tailored to a patient's requirements.[29] Other Queensland companies include 61medical, a subsidiary of Swiss-based 41medical, which develops and produces medical devices. This company was established through an agreement between the Queensland Government, 41medical and 61medical, and is designed to draw upon 41medical's international knowledge and networks to develop Queensland's local medical technology sector.[30] Oventus Medical, another global company with its Australian headquarters in Queensland, supplies 3D-printed oral devices for people suffering from sleep apnea.[31] Finally, Stryker, a global medical technology company that develops a diverse range of medical and surgical equipment, orthopaedic, neurotechnological and spinal products and services, also has a Brisbane office.[32]

Challenges and future opportunities

Engaging stakeholders and managing the pace of technology development and regulation. In the last two decades, rapid advances in technology and materials science have delivered significant benefits to the health sector, however, regulatory frameworks have not kept the same pace of growth. Additive biomanufacturing applications are unfamiliar territory for regulators, which presents significant uncertainties for translating these products into routine clinical practice.[33] The Australian Therapeutic Goods Administration (TGA) currently has limited oversight over custom-made medical devices, including 3D-printed devices, which can be exempt from stringent regulatory processes if they do not contain biological matter.[33] The TGA has proposed changes to the regulatory framework to better categorise the different types of personalised medical devices and reduce potential risks for patients.[34] Greater standardisation of the language and terminology used by the industry would assist in improving the regulatory processes around additive biomanufacturing.[33] A balance also needs to be struck between promoting innovation and ensuring patient safety and efficacy, and this is likely to be best achieved by engaging all stakeholders (e.g. industry, academia and consumers) in developing new regulatory processes.[33]

Optimising access to expertise and hardware for developing prototypes and products. Access to 3D printers is a necessary prerequisite for additive biomanufacturing and a key challenge for companies looking to develop new prototypes and products. In developing new products, researchers and developers need access to a range of printers to trial different approaches and this would be a significant cost for small-to-medium-sized businesses. The university sector has access to a diverse range of 3D printers, and the researchers, designers and engineers who can build the software needed to control them. But much of the great design and engineering work in additive biomanufacturing currently happening in Queensland universities is not being commercialised. Experts suggested that Queensland universities could establish a platform model wherein businesses could develop and scale their products in collaboration with universities, drawing upon their expertise and facilities.

Competing with southern states for research funding. Despite Queensland's strengths in additive biomanufacturing research and other medical technology areas, the state has not been as successful as other Australian states in attracting funding for medical research (see Figure 3). As at 30 October 2020, Victorian institutions and organisations had received the largest share of funding from the Medical Research Future Fund (41.9%), with 15.9% allocated to Queensland. Experts felt more decisive leadership from government, academia and industry is needed to improve the sector's access to federal government investment in medical research and technology. Experts also felt the current level of funding is not sufficient to grow this industry development opportunity, nor to support the university sector and businesses to design, develop and commercialise novel solutions using additive biomanufacturing. Strong leadership would help the sector develop a clear vision and a strategy for how additive biomanufacturing could make a positive contribution to the hospitals of the future.

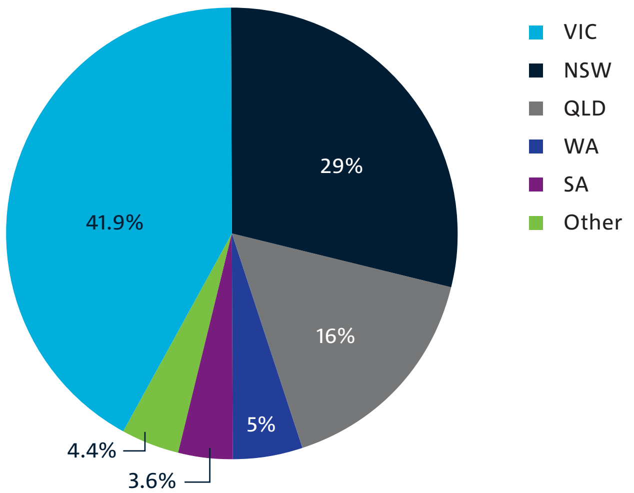


Figure 3. Total funding for successful Medical Research Future Fund grant recipients as at 30 October 2020 by state and territory

Source: Australian Government Department of Health[35]

Note. 'Other' reflects the summation of Australian Capital Territory, Tasmania, Northern Territory and multi-state grants.

Attracting and training skilled workers to support additive biomanufacturing. Queensland has a strong engineering and manufacturing skilled workforce, with 160,695 persons employed in manufacturing (6.6% of the labour force) and 175,332 employed in professional, scientific and technical services (7.2%) as of August 2020.[36] However, few of these skilled workers are focused on biomedical applications. This ready-made talent pool has transferrable skills that could be applied in additive biomanufacturing, but a structured, coordinated approach is needed to support this workforce in transitioning their capabilities for the biomedical sector.[37] Queensland is an attractive location for highly educated, globally mobile scientists, engineers and innovators to live and work,[37] and experts emphasised that these positive lifestyle qualities could be leveraged to attract new domestic and international additive biomanufacturing talent to the state. The post-COVID-19 environment and Australia's relative success in controlling the spread of the virus (ranked in eighth place out of 98 countries[38]) could also present opportunities for the country, including Queensland, to attract prospective international students and workers in relevant capability domains.[39]

Related industry opportunity areas

- **AI-enabled healthcare:** common drivers through the rising demand for healthcare services and opportunities provided by the broader precision-medicine market
- **Green metal manufacturing:** potential reciprocal benefits of growing capabilities in advanced manufacturing and flow-on effects of clean energy developments for additive biomanufacturing
- **Resource recovery technologies:** opportunities to support existing resource recovery efforts by minimising waste in production and reusing materials in additive manufacturing applications
- **Healthcare:** opportunities to support the healthcare sector in managing future demand whilst improving population health outcomes through the personalisation of care
- **Advanced manufacturing:** additive biomanufacturing forms part of Queensland's broader development of its advanced manufacturing capabilities


HA

2 AI-enabled healthcare

	2019	2030
Businesses	**247** businesses	**577** businesses
Direct FTE jobs	**1,174** direct FTE jobs	**2,740** direct FTE jobs
Indirect FTE jobs	**3,673** indirect FTE jobs	**8,575** indirect FTE jobs

AI can be defined as a collection of computational methods that process data and elicit information from solving problems or completing tasks, sometimes without explicit guidance from a human being.[40] It covers fields such as machine learning, computer vision, natural language processing robotics and others.[40] AI is increasingly being applied in healthcare given the growth in data volumes from electronic medical records, wearable devices, imaging and genomics.[41] This technology can be used to provide insights from the cellular to the societal level, identifying disease-causing genes, automating the screening of medical conditions, organising clinical data, identifying disease biomarkers and detecting abnormalities in patient behaviours through remote monitoring systems, amongst many other applications.[41]

Queensland has access to comprehensive clinical data through its integrated electronic medical record (ieMR), along with its high-quality healthcare system and strong translational research institutions and facilities. These comparative advantages put the state in a robust position to explore future AI-enabled healthcare opportunities. AI provides opportunities to use data more intelligently – whether that be clinical data, data collected from patient devices or apps, or data collected from researchers – to improve the efficiency of the healthcare system, reduce costs and improve health outcomes for the people of Queensland and beyond. While there is a growing cluster of AI companies in Brisbane which are using AI for healthcare applications, experts consulted for this report felt AI-enabled healthcare is an underutilised opportunity for Queensland that has strong future potential.

There were 247 AI-enabled healthcare businesses in Queensland as at 30 June 2019, and this is projected to increase to 577 by 2030 (see Figure 4). These could include AI firms that are applying their capabilities in healthcare as well as other domains, or exclusively working in healthcare. These businesses are estimated to account for 1,174 direct FTE jobs and 3,673 indirect FTE jobs for Queensland currently and this is predicted to increase to 2,740 direct and 8,575 indirect FTE jobs by 2030 (see Figure 4). These projections are based on an adjusted 10-year average annual growth rate in firms of 7.2%. To illustrate the potential growth of this sector based on current global growth rates, the number of firms and jobs were also forecast using published global growth estimates. Some estimates suggest that the global market for AI in healthcare is expected to grow at a compound annual global rate of 41.5% from 2019 to 2025,[42] with others predicting a rate of 44.9% from 2020 to 2026.[43] The average of these figures was used to inform the estimate of global growth rates. As seen in Figure 4, the rate of growth in this industry would be exponentially greater if Queensland kept pace with global changes relative to the current growth trajectory.

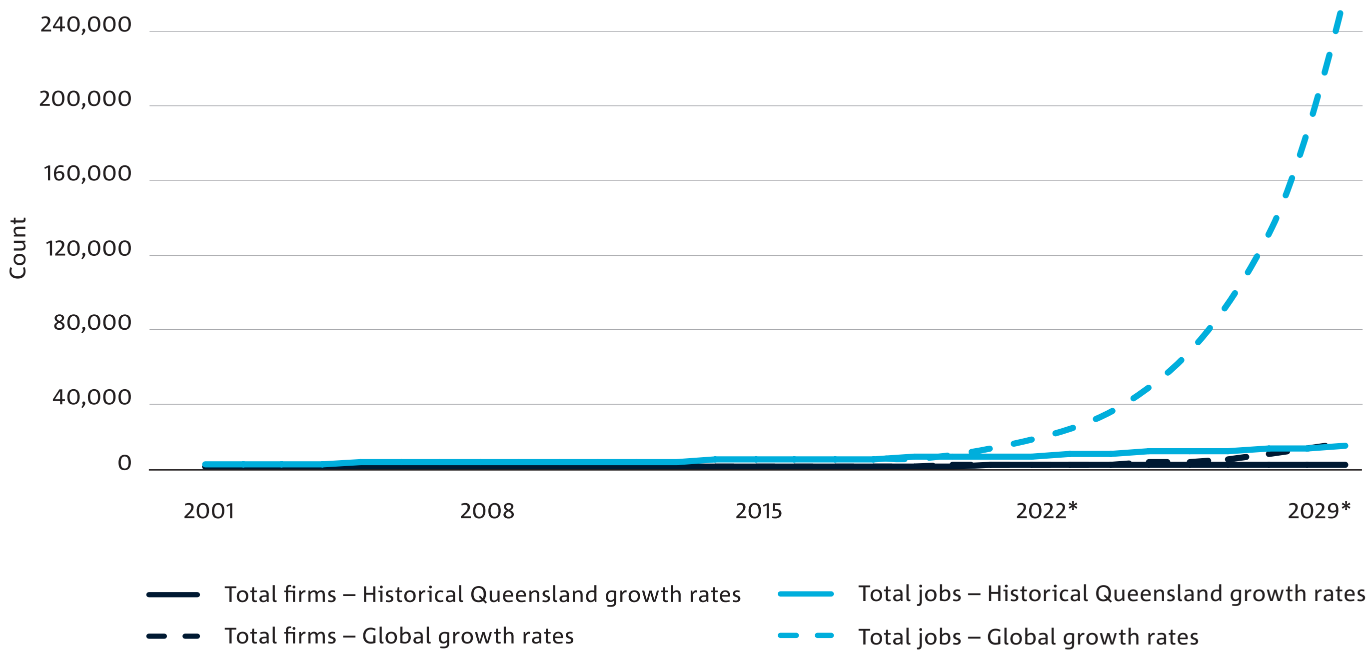


Figure 4. Historical and projected (based on historical Queensland growth rate and global growth rate) number of GST-registered firms and total full-time equivalent jobs (including direct and indirect jobs) in the AI-enabled healthcare industry in Queensland

Note. Years denoted by an asterisk (*) reflect forecasted years.

Why Queensland?

QUEENSLAND'S POTENTIAL AI-ENABLED HEALTHCARE INDUSTRY AT A GLANCE	
Demand drivers	• An increasingly strained healthcare budget and the need to identify opportunities to flatten the expenditure curve whilst improving health outcomes • The potential to use AI to customise medical treatments for chronic conditions to specific individuals and predict the future risk of disease
Supply drivers	• Diverse and strong research capabilities in health, biomedical science and AI, and emerging innovative collaborations with industry which combine these strengths • Significant federal and state public investment in AI and digital health, including the establishment of the Queensland AI Hub • A rich data resource through the ieMR, which could be used to develop AI tools that support better patient and system outcomes • A strong, trusted, high-quality healthcare system, which could be leveraged in digital health initiatives • A growing cluster of AI start-ups in Brisbane, including Datarwe, Maxwell Plus, Biarri Health and Max Kelson, which are using AI for healthcare applications
Challenges and future opportunities	• Raising awareness around potential AI applications by improving the AI literacy of leaders, clinical and non-clinical staff and adopting an 'AI First' strategy • Managing privacy risks by establishing a set of ethical principles for AI in healthcare, which considers fairness, transparency, explainability and trustworthiness • Tapping into a larger international market by partnering across government, industry and academia in significant, high-reward projects • Strategic investment in basic and applied AI research to build the knowledge and capabilities needed to grow AI-enabled industry opportunities

Demand drivers

Increasingly strained healthcare budgets. Healthcare systems across Australia and globally are increasingly strained by a growing demand for healthcare, as reflected by rising healthcare expenditure. The healthcare budget for Queensland in 2019–20 was $19.2 billion, which reflects a $1.1 billion increase from the previous year, and the state's healthcare expenditure has been increasing at a faster rate than its population (average annual growth of 6% versus 1.6% from 2008–18, respectively).[44,45] Although Australia's healthcare expenditure as a share of gross domestic product (GDP) (9.3% in 2019) is below other healthcare systems such as the United States (17% of GDP spent on healthcare in 2019) and the United Kingdom (10.3%), it has been growing at a faster rate than the OECD average (see Figure 5). Increasing demand for healthcare services is being driven largely by changes in treatment patterns (accounting for 48–50% of growth), followed by the demographic shift caused by an ageing population (35–44% of growth).[46,47] Flattening the healthcare expenditure curve and improving health outcomes are key motivators for digital innovations in healthcare.

Growing burden of chronic conditions. The proportion of Queenslanders who have at least one chronic health condition has been increasing (see Figure 6), with the most common conditions in Australia being cardiovascular disease, cancer, chronic respiratory conditions, chronic musculoskeletal conditions, diabetes and mental health conditions.[49] Chronic conditions can have a significant impact on quality of life, productivity and healthcare costs.[50,51] Lifestyle and behavioural factors, like smoking, obesity, physical inactivity and unhealthy diets, can increase the risk of chronic illness,[52] and many of these conditions can be prevented, reduced or improved through appropriate behavioural and environmental changes.[50] AI, combined with access to big data, provides opportunities to improve the customisation of clinical recommendations using longitudinal patient and population-level data.[53] AI could also be used for preventative purposes, using patient data, combined with data from health-monitoring apps and devices and genetic information, to predict future risk of disease.

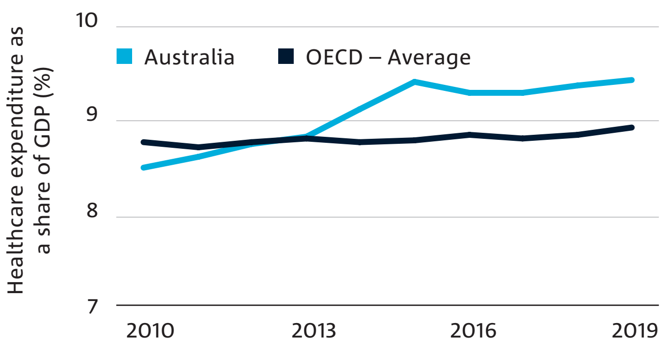


Figure 5. Healthcare expenditure as a share of gross domestic product (GDP)

Data source: Organisation for Economic Co-operation and Development[48]

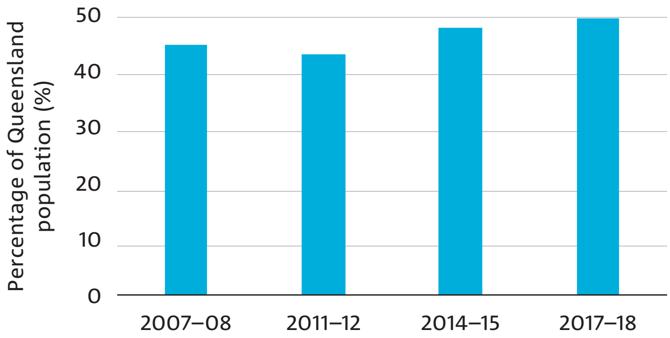


Figure 6. Percentage of Queensland population with one or more reported chronic health conditions

Data source: Australian Bureau of Statistics[9]

Supply drivers

Research capabilities in health, biomedical science and AI research. Queensland has a diverse base of world-class health and biomedical research institutes, facilities and hospitals, which provides the foundations for understanding human health, disease and therapeutic interventions. According to the latest Excellence in Research for Australia outcomes, 9 out of Queensland's 11 universities were rated 'above' or 'well above' world standards for medical and health sciences.[54] Queensland is also home to translational research institutes, such as the QIMR Berghofer Medical Research Institute and the Translational Research Institute, along with hospitals that are actively collaborating with Queensland universities and/or local companies. For example, QIMR Berghofer has partnered with Brisbane-based AI technology company, Max Kelson, precision analytics firm, genomiQa, and genome sequencing company, BGI Australia, along with the Royal Brisbane and Women's Hospital in a $2.6 million project aimed at using AI and whole-genome sequencing to predict patient outcomes of cancer treatment.[55,56] CSIRO's Australian e-Heath Research Centre has also applied AI, in collaboration with Queensland Health and a range of Queensland universities and health services, to improve the scheduling of elective surgery, predict hospital demand and patient deterioration, enhance clinical decision-making and support the early diagnosis of clinical disorders.[41]

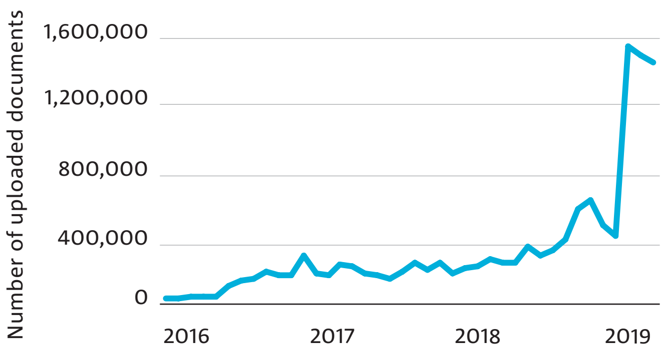


Figure 7. Number of documents uploaded to My Health Record in Queensland, February 2016 to May 2019

Data source: Primary Health Network[66]

Government investment in AI and digital health. In April 2020, the Queensland AI Hub was launched, which was supported by a $5.5 million investment from the Queensland Government.[57] UQ and QUT are founding partners in the hub, alongside a consortium of private-sector partners and members, which aims to bring together capabilities in AI and support businesses in adopting AI and attracting AI talent to Queensland.[57] While the hub has a broad focus, it could support Queensland in building its national and international reputation in AI-enabled healthcare. The Australian Government has also recently announced a $19 million investment over the next 3 years from 2019–20 for medical research projects using AI to prevent, diagnose and treat health conditions, acknowledging the critical role that AI will play in the future healthcare system.[58] This follows on from the Australian Government's previous $55 million investment in the $229 million Digital Health Cooperative Research Centre (CRC).[59] This CRC is supporting a new project between Queensland Health, UQ and the Healthcare Information and Management Systems Society, which aims to develop a digital health roadmap for Queensland and measure the system's current digital ability.[60] This roadmap may provide valuable strategic direction for Queensland's future AI directions in healthcare.

Queensland's advanced digital health records. The volume, velocity and variety of healthcare data is growing at a rapid pace,[61] and the digitisation of medical records is making this data more accessible for quality and system improvements.61 The number of documents uploaded to My Health Record, the national digital health record, in Queensland has grown exponentially since the system was introduced (see Figure 7). Queensland is leading nationally with its $376 million rollout of the ieMR, which aims to improve access to longitudinal patient information, system efficiency and collaboration between healthcare providers.[62,63] To date, the ieMR has been rolled out across 14 hospitals and health centres in Queensland,[64] and with the soon-to-be-completed ieMR rollout in Metro North Health, Queensland will have the most extensive electronic medical record in the southern hemisphere. PricewaterhouseCoopers estimates that the initial ieMR rollout across five Queensland hospitals generated $181 million in financial and economic benefits.[65] The ieMR offers a rich data record, providing Queensland with a unique advantage in developing AI tools to support better system and patient outcomes.

A trusted, high-quality healthcare system. Australia's healthcare system is among the best in the world, second only to the United Kingdom out of 11 countries for overall system performance.[67] Australia's reputation for quality healthcare, along with its strong health and medical research sector, positions the country – including Queensland – in a competitive position to take up the opportunities provided by digital health.[68] With the growing pressures placed on the healthcare system, there is a growing imperative to utilise technology better to continue to deliver the same high standards of care. According to Australia's National Digital Health Initiative, digital health is an underutilised opportunity for the Australian healthcare system, which, if leveraged, could boost the economy through the creation of skilled knowledge-intensive jobs, increase advanced manufacturing capabilities in high-value sensors, wearables, connected devices and software products, and strengthen sovereign resilience and capabilities of the healthcare system.[68] Improving the efficiency of the healthcare system through digital health also has the potential to reduce healthcare costs.

Growing cluster of AI start-ups, some with a healthcare focus. Brisbane's AI scene has grown rapidly in the past couple of decades (see Figure 8). A subset of these companies are focused specifically on AI applications in healthcare, including Maxwell Plus, which is using AI to analyse data for the early detection of prostate cancer.[69] Other companies include Max Kelson, which is using AI in the context of cancer treatment selection (see Strengths in health, biomedical science and AI research driver above),[55,56] and Datarwe, which develops medical research platforms for data on acute-care patients that can be used to develop AI-enabled clinical diagnostic tools.[70] Finally, Biarri Health is using AI algorithms to increase the efficiency of hospitals and has developed tools to improve the rostering of staff, optimise pathology sample deliveries and predict the risk of hospital re-admissions and patient costs from the time of admission.[71] The future growth of these and other AI-healthcare start-ups are supported by IntelliHQ, a Queensland-based not-for-profit organisation that is focused on supporting research, investment and commercialisation of AI applications in healthcare,[72] along with the Queensland Government's recent investment in the Queensland AI Hub.[57]

Challenges and future opportunities

Raising awareness around possibilities of AI. Demand for AI healthcare solutions is currently low and experts noted that there is a lack of awareness amongst clinicians around what is possible with AI. While the majority of Australian healthcare workers have high levels of basic digital literacy,[74] experts felt AI literacy is limited amongst clinical and non-clinical workers. AI literacy is a necessary prerequisite for the adoption of AI and the realisation of the benefits that these technologies can provide.[75] Government could play a role in improving the AI literacy of leaders, clinical and non-clinical staff by offering a comprehensive AI-literacy program that covers data governance principles, basic statistics and algorithmic decision making, data visualisation and storytelling, and provides an understanding of how business and clinical processes could be impacted by AI.[75] Experts also suggested that the Queensland Government could adopt an 'AI First' strategy to accelerate AI adoption in healthcare and beyond, similar to the Digital 1st strategy, which aimed to accelerate the design, development and delivery of digital government services.[76]

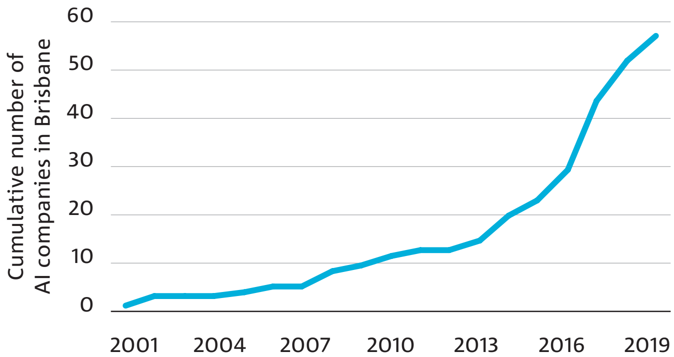


Figure 8. Cumulative number of artificial intelligence (AI) companies in Brisbane

Source: Biarri[73]

Managing data privacy, ethics and governance. Electronic medical records contain highly sensitive data and information that needs to be managed appropriately to protect the privacy of individual health consumers and service providers. There have been several unfortunate events in Australia where health data has been breached, such as a 2016 incident where a sample of de-identified Medicare and Pharmaceutical Benefits claims were released for medical research and policy development purposes, but the Medicare service providers associated with this data could be re-identified.[77] Managing biases, data privacy and consumer and clinician trust are three major ethical challenges facing AI applications in healthcare.[78] The Australian Government has developed a set of eight voluntary principles that should be considered when designing, developing, integrating and using AI systems, such as the fairness, transparency and explainability of the AI system and the accountability of those responsible for developing the AI system.[79] Government could establish a set of AI ethical principles for healthcare specifically, which also considers the trustworthiness of AI systems, ensuring that both clinicians and health consumers have sufficient understanding of how the AI system works to build trust in the technology.[78]

Commercialising AI-enabled healthcare solutions. As the local market for AI-enabled healthcare is small, it would be advantageous to focus on international export opportunities in developing this industry. The global digital-health market was valued at approximately $104 billion in 2019 and this is predicted to increase to $678 billion by 2027.[80] Experts saw value in leveraging Queensland's existing strengths in access to medical data through the ieMR to identify commercial opportunities that use AI to detect disease or identify areas for efficiency gains in hospitals. A number of these technological solutions already exist in the research sector in Queensland, but they are yet to be commercialised. International institutions, such as the industry-funded Cambridge Centre for AI in Medicine, have been successful in developing a portfolio of areas where AI is used to better understand and treat complex diseases, personalise care and establish next-generation approaches to clinical trials.[81] Experts felt that the commercialisation of Queensland's AI applications in healthcare will require strong partnerships between government, industry and academia, and the courage to invest in projects that may be high-risk, but which have the potential for significant pay-offs.

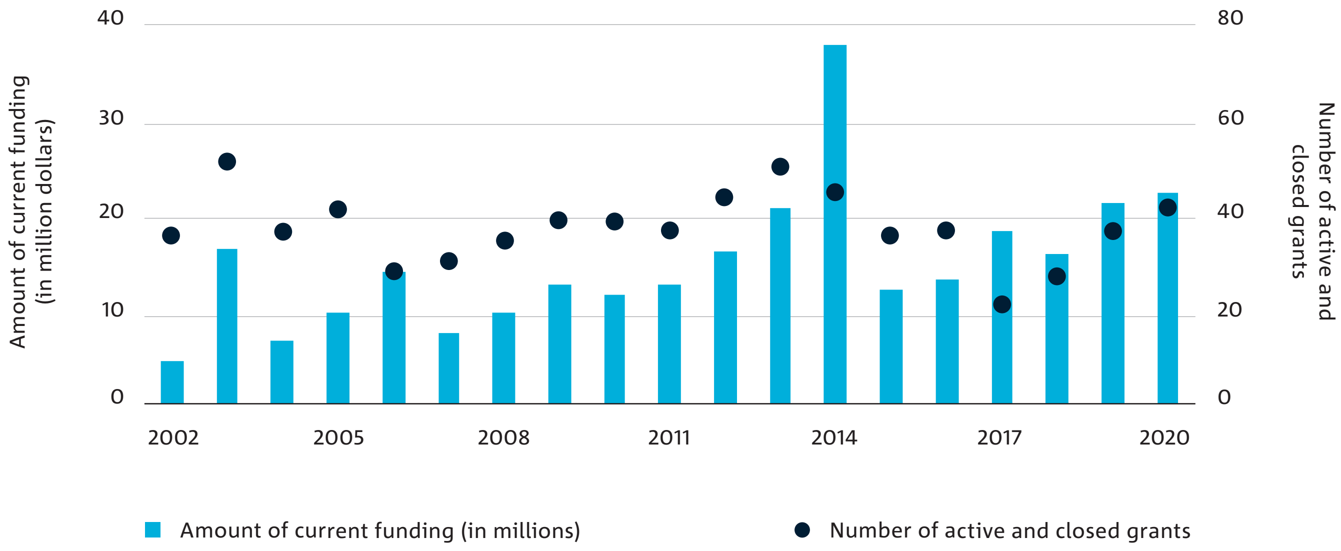


Figure 9. Number and amount of current funding for active and closed grants in artificial intelligence awarded by the Australian Research Council

Data source: Australian Research Council[82]

Note. Grants for inclusion were those that correspond to the following research field codes: 801 (artificial intelligence and image processing) and 802 (artificial intelligence and signal and image processing).

Investing strategically in Australian AI-research to catch up with other countries. Funding for AI research in Australia has fluctuated over the past few decades, peaking at $36.4 million in 2014, which included a $20.6 million investment in the ARC Centre of Excellence for Robotic Vision at QUT (see Figure 9). The average ARC funding for AI research since then has been approximately $16.5 million per year.[82] This level of investment in basic AI research lags behind other countries, such as the United States, which has recently announced an $80 million investment in AI, which will go towards the establishment of five AI-research institutes under the National Science Foundation.[83] Australia also ranks in tenth place in terms of the number of patent families relating to machine learning, with 295 patents filed in Australia as at 2018, compared to other leading countries like China (26,758), the United States (8,064) and South Korea (1,823).[84] Comparatively low investment in basic and applied AI research by global standards presents a challenge for Australia, and indeed Queensland, in growing its AI-enabled industries. Strategic investment and focused AI-related research activities will be needed to expand the knowledge base and capabilities needed to grow AI-enabled industry opportunities, including AI applications in healthcare.

Related industry opportunity areas

- **Additive biomanufacturing:** common drivers through the rising demand for healthcare services and opportunities provided by the broader precision-medicine market
- **Disaster resilience and response technologies:** opportunities to use AI in health-related responses to natural disasters and in managing acute increases in demand for healthcare services in crises
- **Resource recovery technologies:** using AI to support waste-reduction efforts in healthcare, particularly in key priority waste streams like single-use plastics
- **Healthcare:** opportunities to use AI to improve health outcomes, reduce wasteful or low-value healthcare practices and provide services in a more cost-effective manner
- **Advanced manufacturing:** supporting advanced manufacturing capabilities needed in developing robots to assist in the delivery of healthcare services and operations

3 Green metal manufacturing

	2019	2030
Businesses	**523** businesses	**2,413** businesses
Jobs	**2,485** direct FTE jobs	**11,466** direct FTE jobs
	896 indirect FTE jobs	**4,133** indirect FTE jobs

Green metals are manufactured using energy from renewable sources (e.g. wind, solar, hydropower, hydrogen), a process which has the potential to reduce or eliminate carbon emissions associated with metal manufacturing.[85,86] Queensland's natural strengths in having abundant raw commodities, access to renewable energy sources and capabilities in advanced manufacturing provide the state with a strong national, and potentially global, comparative advantage for green metal manufacturing. Although Australia is a leading producer of the two key inputs required in steel manufacturing, namely metallurgical coal and iron ore,[86] it only produces around 0.3% of the world's steel.[87] Australia is also the world's largest producer of aluminium ore (bauxite) and the second-largest producer of alumina (the raw material used in aluminium smelters), but only 15% of this alumina is processed locally into aluminium.[85] High labour costs have traditionally limited Australia's global competitiveness in metal manufacturing, but access to cheap renewable energy could improve its cost-competitiveness for green metal manufacturing.[86] Similar low-carbon-intensity manufacturing opportunities could exist for metals needed to power clean energy technologies.[85]

While 100% renewable energy is the optimal endpoint for green metal manufacturing, other energy sources may be needed to support the transition towards net-zero emissions. For example, steel could be produced using natural gas instead of coal, which is estimated to reduce the amount of emissions by 50%.[86] As the industry develops and as technologies improve, there will likely be opportunities to increase the share of clean energy production to remain globally competitive. National or global shifts away from carbon-intensive energy sources could pose a significant risk to future revenue streams for Queensland's economy given it is a major exporter of fossil fuels, but this transition also presents opportunities to grow and develop new, low-emissions or zero-emissions industries. With global demand for industrial metals continuing to rise and a growing imperative to insure against the risk of declining demand for high-emitting industries, this opportunity presents an attractive area for industry development in Queensland.

There were 523 green metal manufacturing businesses in Queensland as at 30 June 2019 and this is projected to increase to 2,413 by 2030 (see Figure 10). These reflect firms that directly form part of the green metal manufacturing industry, acknowledging that there will be other firms that are associated with the seed industry's value chain, which also create economic and employment opportunities. These businesses are estimated to account for 2,485 direct FTE jobs and 896 indirect FTE jobs for Queensland currently and this is predicted to increase to 11,466 direct and 4,133 indirect FTE jobs by 2030 (see Figure 10). These projections are based on an adjusted 10-year average annual growth rate of 13.3% over the next 10 years. The total jobs estimate for 2030 (15,599) is similar to other estimates provided by the Grattan Institute for green metal manufacturing in Queensland (i.e. 15,000 jobs).[86]

To illustrate the potential growth of this sector based on current global growth rates, the number of firms and jobs were forecast using insights derived from published global growth estimates from a comparable or related sector. In this case, the World Wide Fund for Nature predicts that wind and solar energy production will increase by 5% per year out to 2050.[88] Global primary materials use is projected to increase by 1.5% per year between 2011 and 2060,[89] with the aluminium industry specifically growing by 1.6% per year from 2020 to 2050.[90] Moreover, renewable energy technologies can use up to five times more copper than their conventional counterparts, meaning that the rise of green energy initiatives could spark major growth in the global copper market, which is expected to grow at a 2.6% compound annual growth rate from 2018 to 2027.[91] The average of these figures was used to inform the estimate of global growth rates, which, as shown in Figure 10, is predicted to grow at a slower rate than the historical Queensland growth rate.

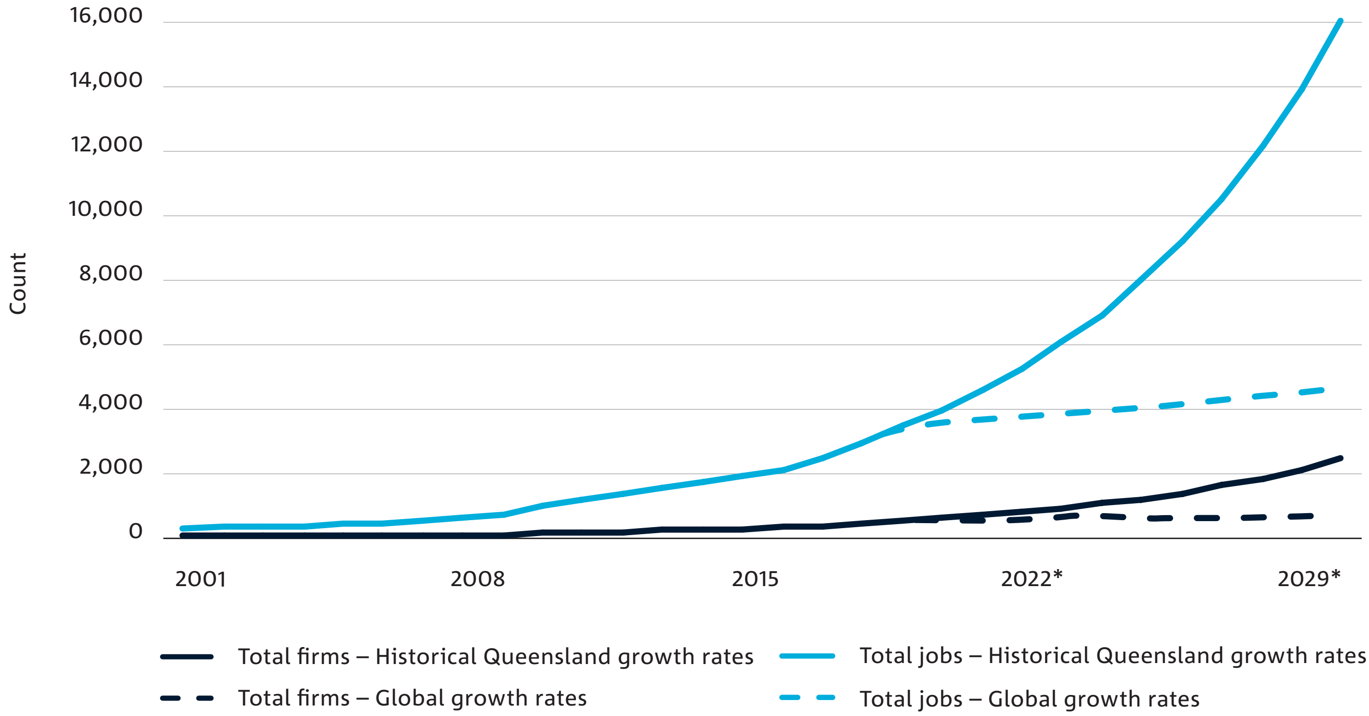


Figure 10. Historical and projected (based on historical Queensland growth rate and global growth rate) number of GST-registered firms and total full-time equivalent jobs (including direct and indirect jobs) in the green metal manufacturing industry in Queensland

Note. Years denoted by an asterisk (*) reflect forecasted years.

Why Queensland?

QUEENSLAND'S POTENTIAL GREEN METAL MANUFACTURING INDUSTRY AT A GLANCE	
Demand drivers	• A global push to decarbonise the economy, driven by consumers, public policy and private enterprises • Demand for low-emissions products, including green metals, from the construction, manufacturing, renewable energy and e-mobility sectors • Large global steelmakers, such as Baowu and SSAB, exploring opportunities to eliminate emissions from metal manufacturing using hydrogen instead of coal • Declining costs of renewable energy, hydrogen fuel cells and hydrogen storage
Supply drivers	• Strong research capabilities in green and low-carbon metals and supporting capabilities in renewable energy and advanced manufacturing • A ready-made workforce for green metal manufacturing in Central Queensland, with opportunities to transition workers from coal mining to metal smelting • Abundant access to renewable energy sources including wind, solar and hydropower • Opportunities for green steel and aluminium manufacturing (both of which have a sizeable carbon footprint), and other metals needed for clean energy technologies • State and national government initiatives to enhance renewable hydrogen production and build a hydrogen industry in Queensland and Australia
Challenges and future opportunities	• High costs of green metals and technical barriers to scaling the industry could be addressed through 'demand–pull' public policy and a green-steel flagship project • Position the state to be nationally and globally competitive through strong leadership that leverages Queensland's comparative strengths

Demand drivers

Global push to decarbonise the economy. A strong driver of green metal manufacturing is national and global commitments to reduce greenhouse gas emissions. As a signatory of the 2015 United Nations' Paris Agreement, Australia along with many other countries has committed to keeping global average temperatures below 2 °C above pre-industrial levels and limit increases above 1.5 °C.[92] The Queensland Government, as with all other states and territories, has also committed to reaching net-zero emissions by 2050 and reducing 2005 level emissions by at least 30% by 2030.[93] This movement to decarbonise the economy is supported by the public, with a 2020 survey finding that 75% of Australian respondents support the 2050 net-zero emissions target and 81% support the accelerated development of new industries and jobs powered by renewable energy.[94] Since metals like aluminium are key inputs into high-end and advanced industries such as electronics and cars, major transnational companies have also made commitments to use a lower-emissions product along their global value chains (see Industries demanding low emissions products driver below), and these companies will likely be willing to purchase low-to-zero carbon emissions materials.

Industries demand low-emissions products. Metals are critical inputs to industries like construction, manufacturing, renewable energy and e-mobility, many of which are taking action to become carbon neutral. For example, the Australian Building Codes Board is exploring potential changes to the National Construction Code in 2022, which would serve to reduce energy use in buildings and the associated greenhouse gas emissions.[95] The constructions sector also has several voluntary standards for sustainability in built environments (e.g. the National Australian Built Environment Rating System),[96] or net-zero emissions buildings (e.g. Green Star).[97] Major car manufacturers have also made ambitious emissions-reduction targets, with Volkswagen aiming to have a carbon-neutral fleet by 2050,[98] and Daimler committing to all new car sales being carbon neutral by 2039.[99] The global energy transition and increased uptake of renewable energy technologies will also fuel demand for low- and zero-emissions metals.[100] Global demand for major metals is set to double or triple from 2010 levels by 2050,[101] and without significant changes in the way metals are manufactured, the emissions will similarly increase.[100] Transnational companies are conscious of supply chain sustainability as a part of their corporate responsibility and are carefully considering their value chains to ensure that carbon-free objectives are met.[102,103]

Global steelmakers looking for ways to reduce their carbon emissions. Queensland's rich endowment of natural resources has provided the state with a comparative advantage in the resources sector, with mining generating $87.2 billion in exports in 2018–19.104,[105] Australia's, and indeed Queensland's, export market for metallurgical coal could be challenged in the future, however, as international companies explore opportunities to reduce the carbon-intensity of steel manufacturing. For example, Baowu, China's largest steelmaker, plans to commercialise the production of 'green' (carbon-free) steel by 2035 by substituting metallurgical coal with hydrogen.[106] Rio Tinto has also partnered with Baowu to explore ways of improving the environmental footprint of its steel value chain.[107] Baowu is in competition with Swedish steelmaker, SSAB, which similarly plans to have market-ready green steel by 2026 and be completely fossil-free by 2045.[108] SSAB forms part of the HYBRIT initiative with Swedish mining company LKAB and energy producer Vattenfall, which has attracted approximately $30 million towards a pilot green-steel production plant.[109] Other European steelmakers, such as ArcelorMittal, Salzgitter, ThyssenKrupp and Voestalpine, are also exploring opportunities to eliminate emissions by substituting coal with hydrogen.[100]

Renewable energy, including hydrogen, getting cheaper and demand increasing. Exploration of hydrogen as an alternative energy source started in the 1970s,[110] but the current renewed interest and investment in hydrogen is motivated by the realisation that it could support global decarbonisation objectives.[111] Moreover, the cost of producing and using clean hydrogen using renewable energy sources has been decreasing, aided by declining costs for solar and wind power, the production of hydrogen fuel cells and hydrogen storage.[112] The future cost-competitiveness of hydrogen will depend on the cost of alternative fuel sources.[112] The cost of producing hydrogen using renewable energy sources is currently greater than using fossil-fuel-powered sources,[113] and this cost gap varies across different applications.[112] While hydrogen is likely to be cost-competitive for use in transport and industrial uses (e.g. refineries) by 2030, it will likely take over a decade for hydrogen to be more economical than coal in steel production.[112] To be competitive globally, green metal manufacturing rests upon access to cheap, clean energy. Other energy sources, such as natural gas, which produces approximately 50% less emissions than coal, may be an alternative fuel source in the interim to support the initial transition to low-emissions metal manufacturing.[86]

Supply drivers

Well-supported research capabilities for green metal manufacturing. Queensland has diverse and relevant research capabilities and industry collaborations, which could form the foundations of a sustainable and globally competitive green metal manufacturing industry. UQ hosts the HBIS-UQ Centre for Sustainable Steel – a collaboration between UQ and leading global steel manufacturer, HBIS – which researches green and low-carbon steel materials.[114] UQ, in collaboration with other interstate university partners, is also part of the Baosteel Australia Joint Research and Development Centre, which explores a range of innovative, strategic focus areas for Baosteel, including low-carbon products.[115] UQ's Dow Centre for Sustainable Engineering Innovation is also exploring innovative approaches for iron ore reduction without producing carbon dioxide (CO_2).[116] Queensland also has broad research capabilities into renewable generation and storage including UQ's Energy Initiative, Griffith University's Centre for Clean Environment and Energy, QUT's Centre for Clean Energy Technologies and Practices and James Cook University's (JCU) College of Science and Engineering. Finally, Queensland has strong research and industry strengths in advanced manufacturing[3] and a globally connected network of regional advanced-manufacturing hubs across the state,[117] which could be critical in improving the cost-competitiveness of Queensland's green metal manufacturing industry.

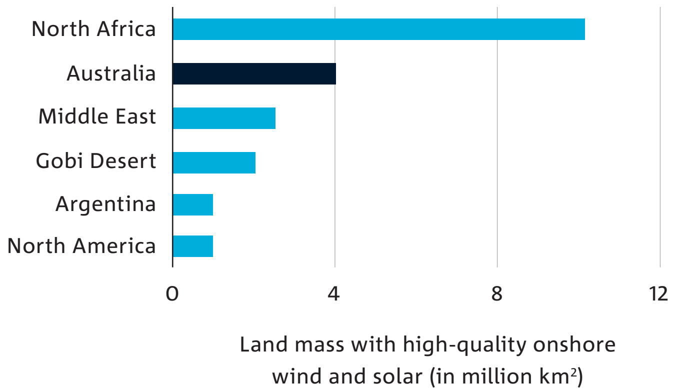


Figure 11. Landmass with high-quality onshore wind and solar (in million km²) in selected regions

Data source: Wood and Dundas[86]

Ready-made workforce for green metal manufacturing. Central Queensland is the ideal location for a green metals industry in Australia, given it has the largest concentration of 'carbon workers' (i.e. persons working in carbon-intensive industries; 23,200 carbon workers), compared with other candidate regions, like the Hunter Valley/Newcastle (16,300).[86] Seventy percent of Central Queensland's carbon workers are employed in coal mining[86] and these jobs could come under threat if global demand for coal declines. While additional training may be required to transition these workers, there is a strong overlap between the skills required in coal mining and in metal smelting, with both sectors requiring technicians, trades workers and machinery operators.[86] If Australia was to increase its share of global steel production from 0.3% to 7% – a feasible target based on current iron ore production – the Grattan Institute estimates that a green-steel manufacturing industry in Australia could generate 25,000 jobs (60% of these jobs would be in Queensland) and $65 million in revenue.[85,86] These exports could come close to providing a substitute for the revenue generated by Australian coal exports ($70 million in 2018–19).[118] Green metal manufacturing could therefore smooth the transition for Queensland in developing a low-emission economy.

Abundant access to renewable energy sources. Australia has a unique advantage in generating renewable energy, with 4 million km² of quality onshore wind and solar, second only to North Africa (see Figure 11). Queensland is also exploring opportunities to generate hydro-electricity from existing dams.[119] These renewable resources offer cheaper energy, providing the state with a global comparative advantage in emerging clean-energy-powered industries.[86] Although there are potential avenues for Australia to export its renewable energy, greater economic returns would likely come from using these energy sources to make low-emissions energy-intensive exports.[86] For example, it may be cheaper to manufacture green steel in Australia using globally cost-competitive renewable energy sources than exporting iron ore and clean energy for manufacturing in other countries.[86] Solar and wind can also be used to produce hydrogen, which, when stored, can be used to fill in gaps in intermittent renewable energy supply.[86] Sun Metals Corporation is a Queensland-based company that is leveraging the green-metal opportunities provided by renewable energy and has invested $5 million in a renewable hydrogen facility following its investment in a 125 MW solar farm, which provides up to 30% of the energy needs of its zinc refinery.[120]

Green metal manufacturing opportunities beyond steel. Aluminium is one of the most high-carbon-intensive metals,[121] and there is growing concern around its carbon footprint.[85] Similar to steel, a fraction of bauxite mined in Australia is translated into its base metal: Australia mined 100 million tonnes of bauxite in 2019, 20 million tonnes of which was refined into alumina, of which only 1.6 million tonnes was smelted into aluminium.[122] The Energy Transition Hub estimates that if 50% of Australia's mined bauxite was converted into aluminium through the addition of 10 renewable-energy-powered smelters, the industry could generate 15,000 jobs and an additional $15 billion in revenue.[100] Queensland has the advantage of having Rio Tinto's fully integrated aluminium supply chain.[123] Rio Tinto has also partnered with global bauxite, alumina and aluminium producer, Alcoa, in a joint venture, Elysis, to eliminate the emissions associated with aluminium smelting,[124,125] and is using hydropower to smelt aluminium in Canada through a $192 million joint public–private investment.[124,126] Similar low-carbon-intensity manufacturing opportunities could exist for other metals needed to power clean energy technologies, such as lithium, cobalt, manganese, nickel, copper and titanium.[85] Queensland's strengths in mining, combined with its abundant access to renewable energy and advanced manufacturing capabilities, could provide opportunities to decarbonise metal supply chains and increase its low-to-zero emissions metals exports.

National and state initiatives in the global hydrogen market. In 2019, the Australian Government released its National Hydrogen Strategy, which outlined a plan to position Australia as a global hydrogen provider by 2030,[112] and has invested $146 million in hydrogen projects.[112] National Energy Resources Australia has also recently announced the establishment of a series of hydrogen-industry hubs across Australia to bring together businesses working on hydrogen technology.[127] This follows other countries such as Japan, China, Germany, the United Kingdom, the United States and New Zealand, which have also released national hydrogen roadmaps and strategies.[128] Queensland, with its access to renewable energy sources and pipeline of renewable energy projects,[112] is the ideal location for renewable hydrogen production. Released in 2019, the Queensland Hydrogen Strategy aims to position the state as a national leader in hydrogen production by 2030,[129] and the Queensland Government has committed $15 million in new hydrogen projects over the next 4 years.[130] Building a hydrogen industry in Queensland could provide new employment opportunities for the 4,181 people employed in the oil and gas sector,[131] given these workers have relevant skills and capabilities that could be transferred into the hydrogen industry.[132]

Challenges and future opportunities

Scaling the industry has technical and cost barriers. The market for green metals is nascent. Although some industries have set net-zero emission targets, green steel is more expensive than 'black steel' produced using conventional fossil-fuel energy sources, meaning that companies must be willing to pay a 'green premium'.[86] However, with innovations in clean energy and manufacturing technologies, and the growing importance of environmental, social and governance factors for investors, the economics of green metals may shift in the future.[133] 'Demand-pull' policies may also be needed to create a sufficient and stable demand for green metals.[134] A carbon penalty could be one potential mechanism, but this would need to be carefully managed given the issues that arose with previous carbon tax attempts in Australia (i.e. increased energy prices for businesses and households).[135] Moreover, the commercial viability of hydrogen-based direct reduction technology (i.e. the process of reducing iron ore to iron metal using hydrogen power) in powering green metal manufacturing has not yet been established and is a significant technical barrier to scaling the industry.[86,136] The Grattan Institute has suggested that government, in partnership with industry, invest in a green-steel flagship project to develop and scale low-emissions steel technologies and improve the economics of green-steel production.[86] Fortescue is already making headway, announcing its plans to establish Australia's first green-steel pilot plant in 2020 and scale this commercially in the next few years.[137]

Positioning Queensland's comparative strengths against national and global competition. BlueScope has partnered with CSIRO and the World Steel Association to explore alternative steel technologies,[125] and plans to invest $20 million in renewable energy infrastructure in New South Wales to support its supply chain.[138] In South Australia, UK-based GFG Alliance has also purchased the Whyalla steelworks and an iron ore mine in the Middleback Range, and aspires to be the world's largest carbon-neutral steel producer by 2030.[139] The plant will be powered by natural gas initially, with long-term plans for solar-powered hydrogen.[140] The Hunter Valley and Newcastle region similarly has a large concentration of carbon workers that could be transitioned into green metals manufacturing.[86] Despite this competition, Queensland has strong comparative advantages for green-steel manufacturing: namely, the largest concentration of carbon workers in Australia,[86] access to critical raw materials and clean energy, advanced manufacturing capabilities and the research capabilities needed to grow this industry. What is missing is leadership to bring these capabilities and resources together and a well-defined plan involving national and international industry and research partners.

Related industry opportunity areas

- **Additive biomanufacturing:** potential reciprocal benefits of growing capabilities in advanced manufacturing and flow-on effects of clean energy developments for additive biomanufacturing
- **Construction technologies:** potential overlap between these industries in terms of their workforce requirements and enabling technologies (e.g. robotics, autonomous systems)
- **Disaster resilience and response technologies:** potential overlap between these industries in terms of their workforce requirements and enabling technologies (e.g. robotics, autonomous systems)
- **Resource recovery technologies:** opportunities to apply resource recovery approaches in recycling and repurposing existing metals like steel and aluminium
- **Advanced manufacturing:** draws upon Queensland's strengths in advanced manufacturing as a key component of the state's comparative advantage in developing a green metal manufacturing sector
- **Mining and resources:** a key input for the green metal manufacturing industry in terms of the raw commodities for metal manufacturing and transferrable workforce skills and capabilities
- **Renewable energy:** supplying the green metal manufacturing sector with clean energy sources and reducing/eliminating emissions associated with metal manufacturing

4 Resource recovery technologies

Most industries generate waste, which is either recovered for other purposes or sent to landfill. As the Queensland population and the economy grows, so too will the amount of waste generated. Queensland's landfill capacity is a finite resource and recent international bans have meant that the state's previous strategies for managing its waste (e.g. exporting recycled materials for processing elsewhere) will not be viable in the future. The waste hierarchy framework can be used to prioritise preferential ways of managing waste, with avoidance of unnecessary resource consumption being the most preferable, followed by reducing, reusing and recycling (recovering and treating waste).[141] Waste disposal is the final option when there is no other viable alternative.[141] The Queensland Government has highlighted organic waste, construction and demolition waste, plastic waste, and electronic and battery waste as priorities for resource recovery given their large contributions to landfill and environmental impacts.[141] These waste streams could be initial focus areas for this industry, which includes companies involved in developing and utilising resource recovery technologies to minimise landfill waste and unnecessary resource consumption.

A circular economy strategy for resource recovery technologies presents opportunities to better manage waste from a variety of streams and convert waste and by-products into recycled material and high-value products. Organic, textile, construction and demolition, glass and plastic waste are some of the key waste streams that are currently being explored as potential candidates for resource recovery and recycling applications. Queensland's research and development into resource recovery is more developed in areas such as the use of organic waste in biofuel applications, compared with the recovery of textile waste, which is complex and requires further investigation. While resource recovery can provide significant social and environmental benefits by diverting waste from landfill and reducing the need to source new raw materials, it can also provide new economic opportunities for Queensland through the development of novel high-value markets.

There were 402 resource recovery technology businesses in Queensland as at 30 June 2019 and this is projected to increase to 927 by 2030 (see Figure 12). These reflect firms that directly form part of the resource recovery technologies industry, acknowledging that there will be other firms that form part of this industry value chain.

2019	2030
402 businesses	**927** businesses
1,910 direct FTE jobs	**4,404** direct FTE jobs
815 indirect FTE jobs	**1,880** indirect FTE jobs

These businesses are estimated to account for 1,910 direct FTE jobs and 815 indirect FTE jobs for Queensland currently and this is predicted to increase to 4,404 direct and 1,880 indirect FTE jobs by 2030 (see Figure 12). These projections are based on the adjusted 10-year average annual growth rate of 7.1%.

To illustrate the potential growth of this sector based on current global growth rates, the number of firms and jobs were also forecast using published global growth estimates from a comparable or related sector. With the global population expected to reach 9.7 billion by 2050,[5] over half of which will be living in cities, managing resources and waste will become a growing challenge. The World Bank estimates that the amount of waste generated globally will grow at double the rate of population growth from 2016 to 2050.[142] With the global population predicted to grow at an average annual rate of 0.73% over the next 30 years,[5] a doubling of this would equate to 1.46% per year – this value is taken as the lower bound of the potential growth in this sector. To gauge the upper bound of growth, we can look to the treatment and recycling of electronic waste, which is estimated to grow at a rate of between 3–5% per year.[143] These figures were used as the basis for the global estimate for the potential growth in demand for resource recovery technologies. As shown in Figure 12, the current rate of change in resource recovery firms in Queensland is predicted to surpass what it would be based on global growth rates if the present trend continues.

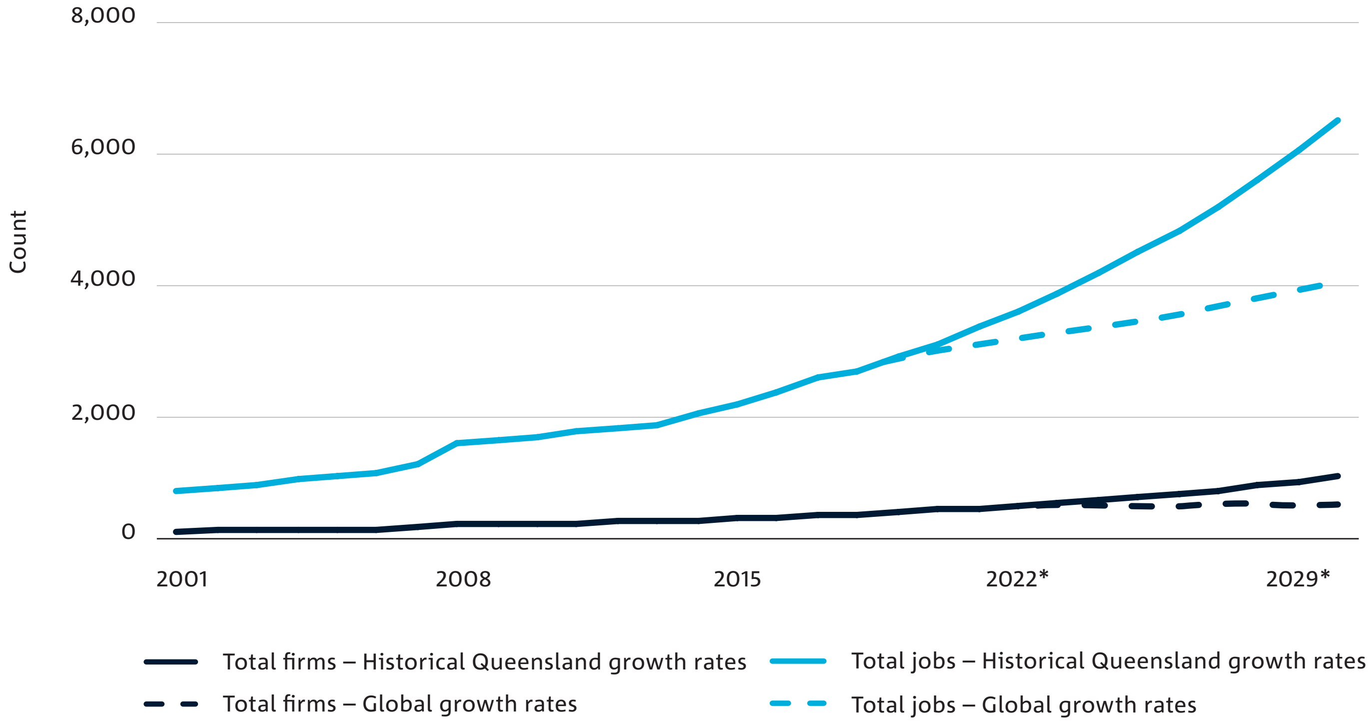


Figure 12. Historical and projected (based on historical Queensland growth rate and global growth rate) number of GST-registered firms and total full-time equivalent jobs (including direct and indirect jobs) in the resource recovery technologies industry in Queensland

Note. Years denoted by an asterisk (*) reflect forecasted years.

Why Queensland?

QUEENSLAND'S POTENTIAL RESOURCE RECOVERY TECHNOLOGIES INDUSTRY AT A GLANCE	
Demand drivers	• A growing waste problem and poor resource recovery rates in Queensland • International bans on waste imports in China and other Asian countries, which have triggered new national bans for Australian waste exports • The potential negative impacts of environmental damage on key Queensland industries like tourism • Enterprises are increasingly conscious of corporate social responsibility practices, which can provide significant financial benefits
Supply drivers	• Significant state and federal public investment in resource recovery research and development, industry development and infrastructure • A strong base of resource recovery research centres and groups across QUT, UQ and USQ working in a variety of waste streams • Local companies exploring innovative resource recovery projects and applications or use of recycled content, including CelluAir, BlockTexx, iOrthotics and Coreo
Challenges and future opportunities	• Working with government, industry and academia to develop a set of use cases that demonstrate the scalability and viability of resource recovery applications • Using sustainable procurement practices and certification to encourage the use of recycled materials, particularly in waste-intensive industries like construction • Addressing skill and workforce gaps in resource recovery by leveraging transferrable skills from other sectors and developing a clear education and training strategy • Expanding resource recovery capabilities to tackle future emerging waste challenges for renewables and other technology-intensive industries

Demand drivers

Poor rates of resource recovery. The total amount of waste generated in Queensland increased by 1.3% from 2017–19, reflecting a similar growth rate to the population (1.7%) and economy (1.1%).[144] Queensland has one of the worst resource recovery and recycling rates in Australia: in 2016–17 Queensland recovered 44.5% of its total waste while South Australia recovered nearly 80%.[145] While the state's waste recovery rate increased in 2018–19 to 48.7% (5.4 million tonnes), 5.7 million tonnes of waste still ended up in landfill.[144] Australia's resource recovery rates also lag behind other OECD countries, with some European countries like Switzerland, Sweden, Denmark and the Netherlands being 100% (or close to 100%) resource recovery (see Figure 13). Ernest and Young estimate that only 1.3% of recyclable material is captured and used in manufacturing and construction in Australia each year, wasting $324 million worth of recyclable material.[146] Continued growth in waste production without significant improvements in resource recovery could present a challenge for Australia's landfill space, which is predicted to reach capacity by 2025.[147]

International waste import bans and national waste export bans. Australia used to export a large share of its recyclable waste to countries like China, Indonesia, Vietnam and India for processing.[149] But in 2017, China announced a ban on foreign waste to protect its environment and public health,[149] and several other Asian countries have since followed suit, with India, Taiwan, Malaysia, Thailand and Vietnam announcing current or planned bans on the import of waste-derived plastics.[150] These bans have had a significant impact and have driven efforts to improve waste management and recycling in Australia. The Australian Government's export ban on waste glass came into force on 1 January 2021, with similar bans planned for waste plastic, paper, and tyres in mid-2021.[151] This export ban forms part of the National Waste Policy Action Plan developed by the Australian Government, which also sets other targets for reducing per capita waste generation, resource recovery rates, phasing out unnecessary plastics and reducing the amount of organic waste in landfill.[152] Federal, state and territory governments in Australia have also committed to having all waste recyclable, reusable or combustible by 2025.[151] These policy commitments could help drive future business and consumer demand for resource recovery.

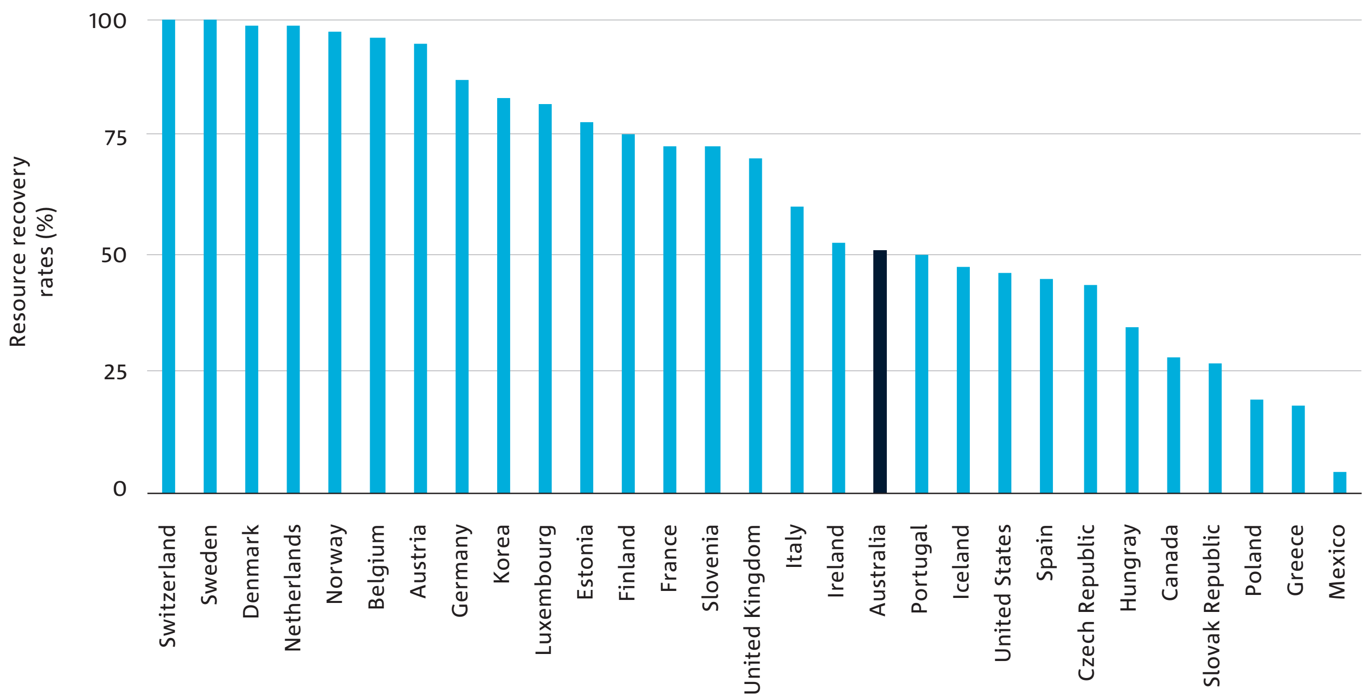


Figure 13. Resource recovery rates across selected OECD countries

Data source: Pickin and Randell[148]

Healthy natural environment key for tourism. Minimising the amount of waste that ends up in landfill or is disposed of inappropriately can reduce the harmful impacts on the environment and oceans. Natural environments are critical to tourism, with 20% of visitors reporting that they would not travel to some regions in Queensland if they were unable to visit a national park.[154] Tourism is a key part of the Queensland economy, contributing a total of 7.7% of total gross state product (GSP) and employing 5.8% of the state's labour force in 2018–19.[153] National parks contributed an estimated $2.7 billion to GSP in Queensland in 2018, providing $6.30 in benefits (e.g. conservation, health, etc.) for every $1 spent on national park visitor management per year.[155] The Great Barrier Reef, Queensland's largest source of tourism revenue, contributed $2.4 billion to the Queensland economy in 2015–16.[156] Environmental damage caused by inappropriate waste disposal and pollutant run-off from agriculture can harm Queensland's natural wonders and impact Queensland's tourism sector. Acknowledging this, Queensland's tourism sector has been a strong proponent of circular practices. For example, Lady Elliot Island Eco Resort has adopted a fully circular economy, generating electricity, desalinating water, treating water and sewage and removing all waste, including returning recyclable materials to the mainland and composting organic matter.[157]

Competitive advantage in corporate social responsibility. Businesses may be motivated to adopt circular practices to save costs. The Queensland Government operates EcoBiz, which is an eco-consulting service for businesses to encourage recycling, reduce waste and be more resource-efficient, and estimates they can save businesses an average of 12% on energy bills, 13% on water bills and 21% on waste bills.158 Through this program, CQMS Razer, a global manufacturer of mining equipment and parts, has increased their recycling rate from 73% in 2012 to 95% in 2014.[159] Another manufacturer, Beaulieu Australia, saved $177,649 per year by changing their production process, resulting in 59% less waste disposal and 16% less energy usage.[160] Some countries have also introduced tax breaks to encourage the recycling or reuse of goods: Sweden offers a reduction in value-added tax from 25% to 12% to encourage people to mend bicycles, clothes and shoes rather than disposing of them.[161] While Queensland does not have similar financial incentives for encouraging recycling practices, the waste levy introduced by the Queensland Government in 2019 is designed to curb landfill waste, particularly from interstate producers.[162]

Supply drivers

State and federal government investment in resource recovery technologies. Resource recovery has attracted significant investment in recent times, both in Queensland and nationally. For example, the Queensland Government committed $100 million to the Resource Recovery Industry Development Program, which aims to divert waste from landfill, reduce waste stockpiling and create jobs.[163] A further $5 million has been invested in the Queensland Waste to Biofutures Fund for early-stage, commercially scalable pilot projects that translate conventional waste streams or biomass into energy, fuel or other high-value products.[164] The first round of this funding (totalling $1.9 million) is anticipated to generate more than $22 million in collective project value.[165] Through the Recycling Modernisation Fund, the Australian Government has also committed $190 million, which is contingent upon co-funding from state and territory governments and industry.[166] This funding is anticipated to generate $600 million in investment in new recycling infrastructure to expand Australia's capacity to sort, process and remanufacture waste.[166] Other noteworthy investments include the $100 million Australian Recycling Investment Fund in clean energy technologies for waste recycling,[167] and the $20 million National Product Stewardship Investment Fund for industry-led recycling schemes.[168]

Research centres focused on recovering high-value products. QUT's expertise in resource recovery research is largely housed in the Centre for a Waste-Free World and the Centre for Agriculture and the Bioeconomy. The first focuses on developing technical solutions to reduce waste and the behavioural, industrial and policy changes needed to support the circular economy.[169] The second researches bioprocessing agricultural by-products and waste into high-value products (e.g. chemicals, resins, coatings and pharmaceutical ingredients) and tests the industrial scalability of biorefinery processes.[170] Researchers from UQ's Australian Institute for Bioengineering and Nanotechnology are also developing methods for converting agricultural waste biomass into high-value chemicals for food production, pharmaceuticals and agriculture.[171] Other work at Bond University, in collaboration with Griffith University, UQ and the geopolymer concrete company, Wagner, is exploring ways to develop ecological construction materials derived from agricultural waste.[172] Finally, the University of Southern Queensland's (USQ) Centre for Agricultural Engineering is developing innovative, on-farm approaches for converting organic waste into high-value fertilisers.[173] QUT, UQ and USQ – along with the Queensland Government – are also partners in the Fight Food Waste CRC, which is focusing on reducing waste from food supply chains as one of its key outcome areas.[174] These capabilities could support the development of new technologies and commercial pathways for generating new value from waste.

Growing base of resource recovery companies. The 2019 *New Smarts* report highlighted Queensland's strong base of commercial biorefineries,[1] and since then, six additional biowaste projects have been funded under the Queensland Government's Waste to Biofutures Fund. These include $500,000 towards AJ Bush & Sons and BE Power Solutions' $11 million biogas-solar power plant, which will convert biogas from meat processing into electricity,[175] and $363,000 towards Energy360's $1.9 million pilot biogas facility that will convert organic waste into fertiliser and power for electric vehicles.[176] Beyond biofuels, Queensland is also home to CelluAir, a joint venture between QUT and Innovyz, an advanced manufacturing incubator, which has converted agricultural waste into a virus-filtering mask material,[177] and BlockTexx, a textile recycler that has pioneered an innovative method of separating cotton and polyester from textile waste back to their raw materials.[178] iOrthotics are also using recycled materials in 3D-printed orthotics, which use around 99% fewer resources than traditional polypropylene devices (developed in collaboration with UQ).[29] Finally, Queensland is home to Coreo, which works with clients to action their circular economy aspirations and has developed a roadmap for Australia's first circular economy master-planned community, Yarrabilba.[179]

Challenges and future opportunities

Presenting strong use cases for the industry. Queensland lacks use cases that demonstrate the potential return on resource recovery investments. However, there is an expanding number of biorefineries in Queensland and these could form the foundation for future use cases for the industry. Experts consulted for this report felt the rate of change in resource recovery is incremental and the strategic relevance of sustainable practices is currently missing from government support for business development. Experts argued for the need for government, industry and academia to come together to further develop and demonstrate the industry-level scalability and viability of resource recovery opportunities.[180] Without this, companies will be hesitant to invest in resource recovery and the changes that are required to embed these technologies and processes in their core business. ASPIRE (the Advisory System for Process Innovation and Resource Exchange) is an online marketplace developed by CSIRO that aims to connect businesses and other parties with unwanted discarded materials, opening up novel opportunities to reuse and remanufacture.[181] Sufficient economic, policy and regulatory frameworks for waste and resource recovery are also lacking in Australia and this is limiting certainty, innovation and investment in the sector.[180] Greater harmonisation of the state-level regulatory framework is also needed to support growth in the resource recovery sector.[182]

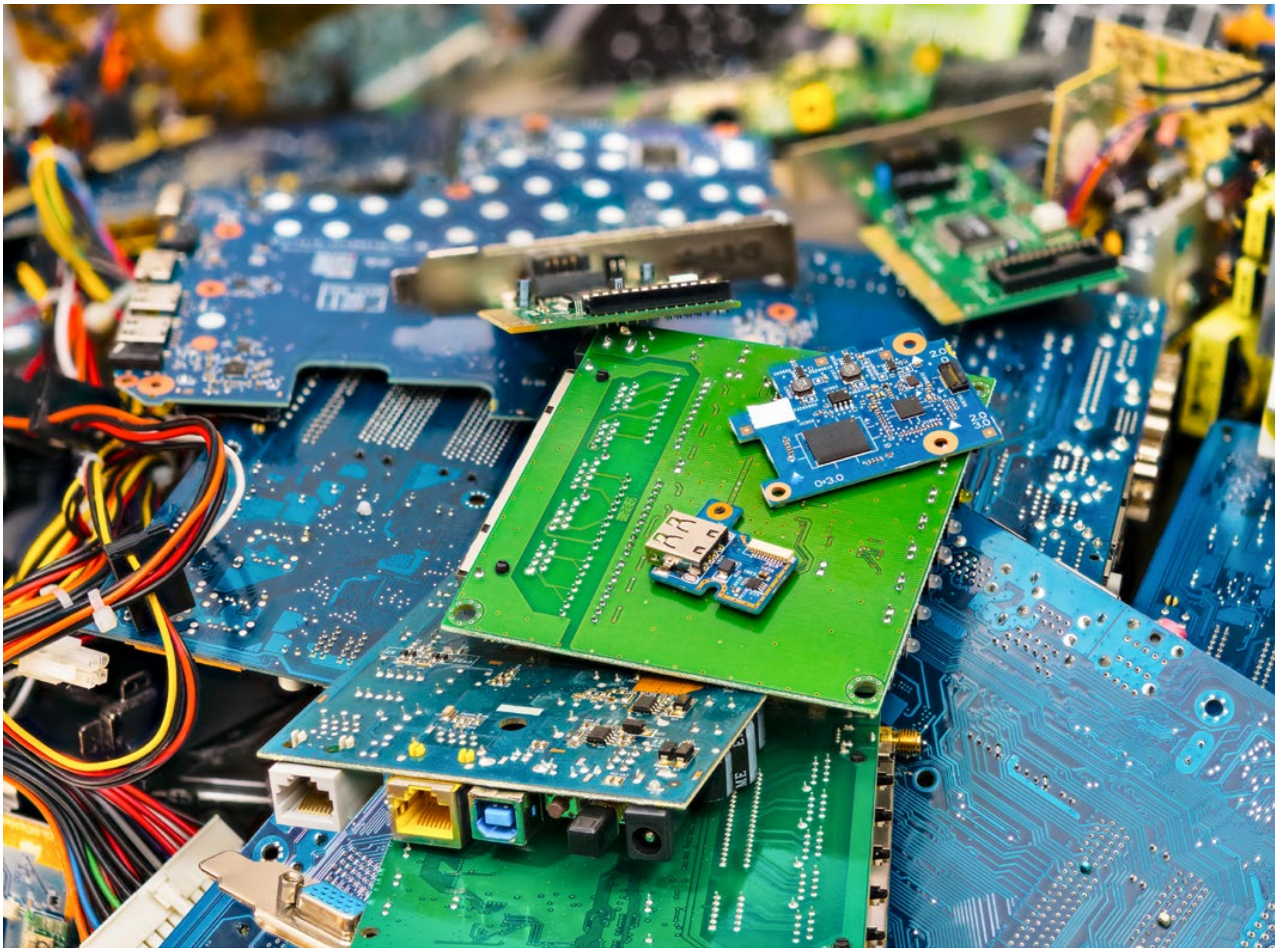
Using sustainable procurement policies and practices to address demand constraints. Successful projects tend to be small scale and focused on niche consumer markets, which can make them difficult to scale when consumer demand is low. Although 55% of online consumers would be willing to pay more for products and services from companies that have a positive social and environmental impact,[183] consumer attitudes around environmentally consciousness and sustainability do not always translate into purchasing behaviour.[184] Acknowledging that the Australian market of recycled productions is small, the Australian Government's National Waste Policy Action Plan 2019 plans to stimulate use of recycled content by government and industry through sustainable procurement practices and policies.[152] Similar procurement policies could also be used to stimulate the consumption of recycled materials in Queensland.[185] Certification is another mechanism that could support the adoption of recycled materials, adding value by verifying the source and/or quality of the recyclable material. Demand for this industry will likely come from the construction sector, which spent $2 billion on waste collection, treatment and disposal services in 2018–19.[186] This could be a key sector for the resource recovery technologies industry to engage in developing future markets, potentially through government-supported partnerships or projects to form the bridge between large construction corporates and resource recovery technology start-ups.

Bridging the skills and workforce gap. Resource recovery is not often the core business of organisations, so they need to outsource these capabilities, but experts reported that there is a lack of skilled suppliers. An analysis of 11 countries found that, despite ranking highly on measures of environmental performance, Australia ranks poorly when it comes to having comprehensive and coordinated approaches to skills for circular economy jobs.[187] Although the Queensland Resource Recovery Industries roadmap highlights the need to upskill the workforce as part of developing this industry,[141] no dedicated upskilling programs have been established nor is there a clear strategy around the education and training of this industry's future workforce. Workers in the mining, construction, manufacturing and transport industries possess the soft and technical skills that will be needed in the circular economy,[187] but the capacity of existing workers to take up these new job creation opportunities will be conditional on tailored education and training programs to help them make the transition.

Expanding resource recovery research for emerging industries. Queensland's resource recovery research covers a diverse range of resource streams including agricultural waste, construction and demolition waste, and waste glass, plastic, textiles, and organics. But less work is focused on recovering resources from waste in emerging industries like renewables and other technology-intensive industries. Battery waste is a growing problem, with the amount of lithium-ion battery waste generated in Australia expected to increase from 3,300 tonnes in 2016 to at least 100,073 tonnes per year by 2036.[188] The majority of this e-waste ends up in landfill (98%),[188] and this situation is likely to worsen as uptake of portable devices and electric vehicles increase.[189] CSIRO estimates that between $813 million and $3 billion of recoverable lithium-ion batteries currently end up in landfill189 – a sizeable opportunity that Queensland could have a stake in. Photovoltaic systems are another growing waste issue, with 83% of solar panel materials currently not recycled and 100,000 tonnes of solar panel waste expected in Australia by 2035.[190] QUT is a partner in the Future Battery Industries CRC,[191] which could serve as a collaborative platform for building up Queensland's research into resource recovery for batteries and other forms of e-waste.

Related industry opportunity areas

- **Waste management, treatment and remediation:** supporting existing waste management approaches by reducing landfill waste and stimulating growth in the recycling sector
- **Additive manufacturing:** opportunities to support existing resource recovery efforts by minimising waste in production and reusing materials in additive manufacturing applications
- **AI-enabled healthcare:** using AI to support waste reduction efforts in healthcare, particularly in key priority waste streams like single-use plastics
- **Green metal manufacturing:** opportunities to apply resource recovery approaches in recycling and repurposing existing metals
- **Agricultural sensors and automation:** agricultural waste can be used to produce new high-value products and these technologies could support the monitoring and collection of waste
- **Supply chain provenance technologies:** opportunities to use supply chain technologies to track the end-to-end lifespan of recyclable materials
- **Disaster resilience and response technologies:** the e-waste generated by this sector could be repurposed through resource recovery processes
- **Construction technologies:** the e-waste generated by this sector could be repurposed through resource recovery processes
- **All other traditional sectors in the Queensland economy** (e.g. retail, hospitality, agriculture, mining, construction, tourism, etc.), which have a waste footprint that needs to be effectively managed to protect Queensland's finite landfill resources



5 Microalgal and macroalgal resources

Queensland has the natural resources (i.e. sunlight, water and nutrients) and expertise needed to grow algae, from the microscopic to macro scale. Algae offers a diverse range of opportunities to develop high-value products, including functional foods, livestock feed, biofertlisers, biofuels and therapeutics, as well as providing low-cost solutions for remediating municipal and industrial wastewater.[192] Algae applications also have the potential to support the decarbonisation of existing sectors, like agriculture and energy, and have been shown to sequester CO_2 from the atmosphere.[193] Growing an algal industry in Queensland has the added advantage of not competing with existing agricultural practices, in that it does not require arable land and can grow in saline or contaminated water.[192] Although Queensland does not currently have strong, established algae markets, there is a good case for opportunities in algae-based animal feedstock and for the state to leverage its proximity to Asia to service existing seaweed consumer markets in the near-term, with further expansion over a longer period.

Queensland has deep scientific expertise in two broad streams of algal research – microalgae (single-celled green algae) and macroalgae (including seaweed) – covering a range of production species and algal applications. Microalgae and macroalgae reflect two different types of algae that differ in their scale and their underlying technologies but have some overlap in their potential benefits and impacts. While Queensland, and Australia more broadly, has a long history of algae-related research, particularly into biofuels, industry applications and companies are still emerging.[192] Algae-related applications present opportunities for Queensland to develop solutions to global challenges around food, water and energy production, whilst also mitigating emissions. Algal industries also present strong regional development opportunities , with the whole value chain, from production to manufacturing to consumption, based in regional Queensland.

	2019	2030
	103 businesses	**326** businesses
	489 direct FTE jobs	**1,549** direct FTE jobs
	117 indirect FTE jobs	**369** indirect FTE jobs

There were 103 microalgal and macroalgal resources businesses in Queensland as at 30 June 2019 and this is projected to increase to 326 by 2030 (see Figure 14). These reflect firms that directly form part of the microalgal and macroalgal resources industry, acknowledging that there will be other firms that form part of this industry's value chain. These businesses are estimated to account for 489 direct FTE jobs and 117 indirect FTE jobs for Queensland currently and this is predicted to increase to 1,549 direct and 369 indirect FTE jobs by 2030 (see Figure 14). These projections are based on the adjusted 10-year average annual growth rate of 9.9%. To illustrate the potential growth of this sector based on current global trends, the number of firms and jobs were forecast using insights derived from published global estimates. Some estimates predict that the global market for algae will grow at a compound average annual rate of 6.2% between 2020 and 2027,[194] while other sources place the growth at 7% between 2019 to 2024.[195] An average of these two estimates was used as the global growth rate estimate for this sector. As shown in Figure 14, the projected rate of growth based on global estimates results in more conservative estimates for firms and jobs out to 2030, compared with those based on historical Queensland data.

Figure 14. Historical and projected (based on historical Queensland growth rate and global growth rate) number of GST-registered firms and total full-time equivalent jobs (including direct and indirect jobs) in the microalgal and macroalgal resources industry in Queensland

Note. Years denoted by an asterisk (*) reflect forecasted years.

Why Queensland?

QUEENSLAND'S POTENTIAL MICROALGAL AND MACROALGAL RESOURCES INDUSTRY AT A GLANCE	
Demand drivers	• Rising demand for food and energy as the global population grows, with the potential role of algae in meeting this future demand • Intergovernmental commitments to curb greenhouse gas emissions and the opportunities to use algae to sequester human-driven CO_2 emissions • Environmental footprint of the livestock sector and the opportunities to use seaweed as an alternative animal feedstock that reduces emissions • Growth in global seaweed market and the potential to increase Australia's share by addressing current regulatory and research funding barriers • Rising demand for water and the opportunities to use algae to bioremediate municipal, industrial and aquaculture wastewaters
Supply drivers	• Local access to the non-arable land, water, nutrients and sunlight needed to grow algae • Leading research capabilities in microalgal and macroalgal applications across JCU, UQ and USC, as well as a research and development foundry, Provectus Algae
Challenges and future opportunities	• Establishing a 5-year roadmap for algal industries, which is currently missing from relevant government strategies • Building an innovation ecosystem of mature firms, start-ups and incubators for algal industries by attracting leading international firms and developing applications through innovative commercialisation hubs • Tapping into larger, established seaweed markets for human food applications, while establishing local animal feedstock opportunities in the short term

Demand drivers

Rising demand for food and energy production. The global population is currently at 7.8 billion and is forecast to reach around 9.7 billion people by 2050,[5] requiring 50% more food under a business-as-usual future (relative to 2012 levels)[196] and 50% more energy (relative to 2019 levels).[197] Seaweed and other algae-based products could play a role in meeting future nutritional needs of the global population, given it contains a range of vitamins, minerals and compounds that could support the health and well-being of humans and animals.[198] Consumer demand for new protein sources and health supplements, and concerns around food security are two primary factors driving growth in the seaweed aquaculture industry in the United States.[199] QPonics Limited, a Queensland-based company, has a pilot algae farm in Brisbane that is already using algae to produce high-value nutraceuticals and food supplements.[200] Microalgae feedstocks can also be used to generate a range of fuel sources using solar energy and CO_2, helping to support the growing energy needs of the global population and economy.[201] Experts consulted for this report predicted that food and animal feedstock commercial applications for seaweed will be achievable in the next 5–10 years, with others likely to emerge beyond the next decade.

Ability of algae to absorb carbon from the atmosphere. Recent estimates from the Intergovernmental Panel on Climate Change suggest that global net anthropogenic (human-caused) CO_2 emissions will need to decline by 45% by 2030 (relative to 2010 levels) to reach net-zero by 2050 and keep global warming close to 1.5 °C.[202] Australia, along with over 190 other countries, is a signatory of the 2015 United Nations' Paris Agreement.[92] There is growing public support for emissions-reduction efforts, such as renewable energy, with 84% of Australian respondents supportive of clean energy sources like wind and solar over traditional energy sources in 2018 (up from 81% in 2017).[203] There are international efforts to accelerate the pathway to carbon neutrality too, such as the recent plans announced by an EU-wide partnership to develop clean hydrogen fuel technologies.[204] Microalgae and macroalgae can efficiently convert sunlight, CO_2 and water into a range of food, energy and other high-value products.[205] Macroalgae in particular has been shown to be effective in sequestering carbon and could play a valuable role in ameliorating the impacts of human-driven CO_2 emissions.[193]

Using algae to reduce the carbon footprint of livestock. Queensland's agriculture sector generated 21.2 million tonnes of CO_2 equivalent in 2018, which makes up 12.3% of the state's total emissions.[206] Three-quarters of Queensland's total agricultural emissions come from livestock enteric fermentation,[206] which produces methane emissions from animals such as cattle, sheep, horses, goats and pigs.[207] Researchers from JCU, the University of the Sunshine Coast (USC) and CSIRO have identified a particular seaweed, *Asparagopsis*, which, when added to cow feed, can close-to-eliminate methane production.[208] USC estimates that if Australia could produce enough seaweed for every cow, national greenhouse gas emissions could be reduced by 10%.[198] CSIRO has recently established the FutureFeed company, backed by $13 million in investment, which plans to commercialise livestock feed additives made from Asparagopsis.[209] Given beef cattle production is Queensland's largest agriculture sector and the state is Australia's largest producer of beef (49.8% of meat cattle in 2018–19),[210] addressing the emissions associated with beef production will be a key part of promoting a more sustainable future industry.

Growth in global demand for algae products. The global seaweed market was valued at approximately $84 billion in 2019 and is estimated to exceed $121 billion by 2026.[211] There are well-established seaweed industries in Asia, including in China and Indonesia, with emerging sectors in the United States and Europe.[212] The European Union has invested approximately $18.4 million from 2017–20 in the GENIALG project (GENetic diversity exploitation for Innovative macro-ALGal biorefinery), which reflects a consortium of industry and academic experts in six countries and aims to boost the seaweed industry in Europe.[213] By comparison, the Australian seaweed market is small, currently valued at $3 million, and Australia imported around $40 million of seaweed in 2017–18.[214] AgriFutures estimates that if current regulatory and technical barriers in the Australian seaweed industry are addressed (e.g. regulatory approval for large ocean leases and insufficient research and development funding to build the necessary knowledge base), the gross value of production of the industry could grow to $100 million and generate 1,200 direct jobs by 2025, increasing to $1.5 billion in value and 9,000 direct jobs by 2040.[214]

Rising demand for water and solutions for wastewater. Seaweed can absorb large quantities of CO_2, nutrients (e.g. nitrogen) and heavy metals from water, making it an effective form of wastewater treatment.[214] Queensland is home to Pacific Bio – one of the two land-based seaweed operations in Australia – which uses native green macroalgae to remove nitrogen and phosphorus from municipal, industrial and aquaculture wastewaters.[215] This technology was developed in collaboration with researchers from JCU,[215] and has been used to demonstrate the potential for net-zero-waste prawn farming in North Queensland.[216] Seaweed is also effective in mitigating coastal eutrophication (i.e. harmful algal blooms arising from excessive nutrient pollution in coastal waters).[217] Similarly, microalgae can be used to remove unwanted nutrients from wastewater in open ponds,[218] and Queensland Urban Utilities has collaborated with researchers at UQ to test the viability of using microalgae-based technologies as a natural form of wastewater treatment.[219,220] BHP has also partnered with several US universities to explore the potential use of algae and plants in remediating soil and water affected through uranium mining.[221] With water demand predicted to grow at a faster rate than the global population or economy,[222] algae could play a role in future water security.

Supply drivers

Abundant resources for algal production. Seaweed can be grown in land-based operations or the ocean, with regional Queensland identified as one of the candidate locations in Australia for seaweed farming.[214] Microalgae also does not require fertile or arable land, meaning that algaculture production should not compete with existing agricultural activities if managed appropriately.[223] An analysis of selected countries found that many of them, including Australia, would be able to supplement 30% of their fuel consumption by using microalgae produced on non-arable land.[224] Other key inputs for algae include salt or freshwater, nutrients and year-round sunlight.[223] Queensland has abundant access to these resources with its long coastline and access to saline water resources.[205] The state also has a natural advantage in generating solar energy, with an average of around 8 daily sunshine hours in Brisbane, compared to south-eastern capital cities (e.g. 7 for Sydney and 6 for Melbourne).[225] Australia has strong potential for growing a globally competitive microalgae industry, with a simulation analysis estimating the potential microalgae lipid productivity in Australia (as measured in Learmonth, Western Australia) amongst the top producing countries (see Figure 15). These local assets could support the state in attracting international algae firms and exporting algae products globally.

Diverse capabilities in microalgae and macroalgae research. JCU has world-leading capabilities in the development of novel food, energy and health products from microalgae and macroalgae.[226] For example, the Centre for Macroalgal Resources and Biotechnology produces macroalgal biomass in a cost-effective and scalable manner for the bioremediation of agricultural, industrial or municipal wastewaters and development of high-value plant, animal and human health products.[227] UQ's Centre for Solar Biotechnology has a diverse microalgae research portfolio, exploring applications for land management, water treatment, animal feedstocks, infrastructure and built environments, functional foods and fuel production.[228] USC's Seaweed Research Group is a multidisciplinary group that is leading research into the environmental, economic and social benefits of seaweed,[198] including the use of seaweed in cattle feedstock to reduce methane emissions.[229] Finally, biotechnology start-up, Provectus Algae, has a research and development foundry based on the Sunshine Coast where it is developing a range of biosynthetic solutions using algae.[230] These capabilities provide a rich knowledge base for future algae-related commercial applications.

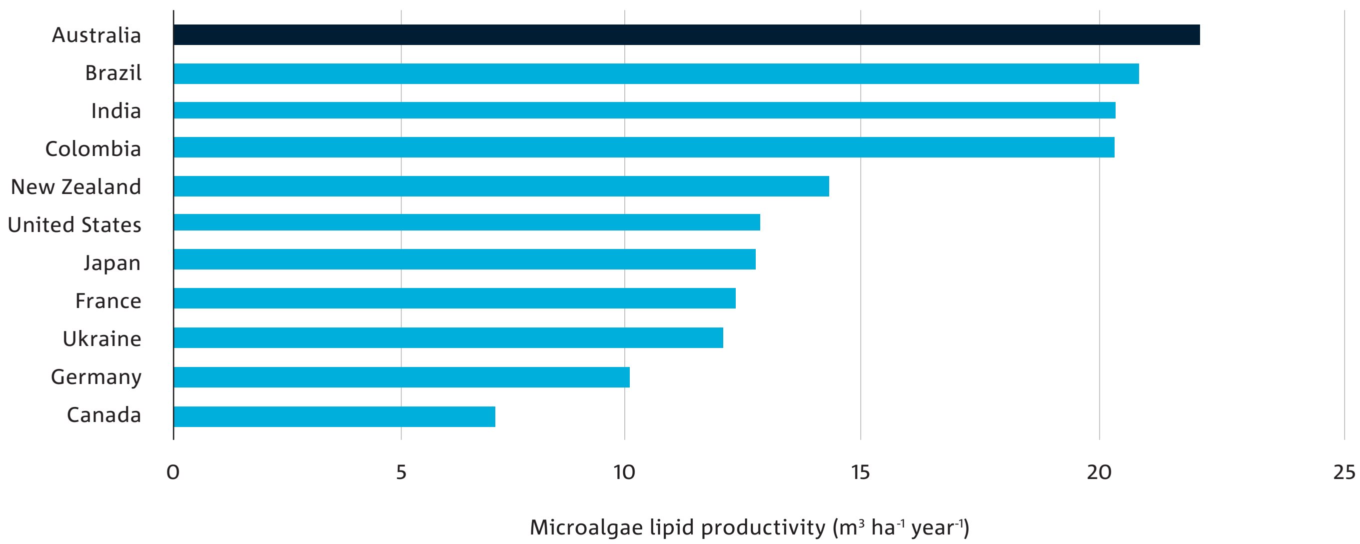


Figure 15. Estimated potential average microalgae lipid productivity across selected countries, 2014

Data source: Moody, McGinty and Quinn[224]

Challenges and future opportunities

Aligning the policy environment to support industry growth. Across Australia, state and federal governments have taken different approaches to climate and energy policies. All state and territory governments have committed to achieving zero net emissions by 2050,[231] but this target is not reflected nationally.[232] Experts felt this discrepancy creates uncertainty for industry and limits their willingness to invest in algae-related technologies and other emissions-reduction technologies. Government commitment to developing algae industries is also missing from relevant agriculture, aquaculture, biotechnology and advanced manufacturing strategies. A national plan for algae industries, similar to the National Aquaculture Strategy,[214] would help promote these emerging aquaculture industries. Australia21, an independent think tank, also suggested the need for a 5-year roadmap for the algal industry in Australia to better characterise the critical success factors needed to develop this nascent industry.[192] Strategies around developing algae industries in Queensland should consider a holistic approach, from the regulatory framework for new farms, which can cause a significant burden for industry,[214] to support for hatchery development for seed stock, which has shown to be successful in growing this industry internationally.

Building solid business models. While Queensland has strong algae research and commercialisation capabilities, it has not been able to link these two together to translate this opportunity into application. To build business confidence, encourage investment and guide government policy, a greater understanding needs to be developed around which technologies are most suitable for particular products and applications, their feasibility and value (including the economic, social and environmental impacts). An ecosystem of mature, established firms, technology start-ups and incubators is also needed to support the experimentation and translation of ideas into commercial realities. Queensland could leverage its natural advantages, research and infrastructure to attract leading international firms to build this innovation ecosystem. Moreover, novel approaches for commercialising nascent innovations could also be used. Examples include the Creative Destruction Lab, which is a not-for-profit organisation funded by a consortium of universities in Canada, the United States and Europe that focuses on scaling seed-stage science and technology companies,[233] or hubs similar to the Advanced Robotics for Manufacturing (ARM) Hub,[234] where algae start-ups could work alongside researchers to develop and commercialise emerging algae-related innovations.

Developing and establishing seaweed products for local and international markets. Seaweed and other forms of algae are not common elements of a Western diet, with a 2017 survey of Australian consumers finding that only 37% had regularly eaten seaweed in the past 12 months.[235] This is shifting though, with seaweed becoming increasingly common thanks to popular media, restaurant menus and online recipes.[235] Seaweed is already a significant element of Asian diets, including in countries such as China, Japan, Korea and the Philippines.[236] With its proximity to Asia, large landmass and suitable climate for growing seaweed and other types of algae, Queensland has a unique advantage in tapping into Asia's thriving seaweed market. The strategic focus of the algal industry will differ across products and applications. While demand for seaweed for human consumption may be more export-focused, there will likely be strong domestic (and potentially international) demand for seaweed applications for animal feedstock and fertiliser, given Queensland's strong livestock sector. Further public and private investment will likely be needed to develop and establish these seaweed market opportunities for Queensland, with AgriFutures estimating that approximately $8.1 million will be needed to support 2 years of critical research, development and experimentation activities in developing Australia's seaweed industry.[214]

Related industry opportunity areas

- **Agriculture and aquaculture:** potential consumers of microalgal and macroalgal products (e.g. animal feedstock, fertiliser)
- **Advanced manufacturing:** advanced manufacturing capabilities needed to translate microalgae and macroalgae into high-value food, energy, pharmaceutical and nutraceutical products
- **Pharmaceuticals:** potential opportunities to diversify the existing pharmaceuticals sector by using algae as a novel input
- **Renewable energy:** potential opportunities to diversify the existing renewable energy sector by using algae as a novel input
- **Waste management, treatment, and remediation:** supporting existing waste treatment and remediation processes, particularly in managing municipal, industrial and aquaculture wastewaters

6 Agricultural sensors and automation

Emerging digital technologies are transforming the agriculture industry, providing new opportunities to improve the productivity and efficiency of the sector and minimise harmful impacts on the environment. These technologies also provide opportunities to address challenges facing the sector, such as seasonal labour shortages. Some of these technologies include the Internet of Things (IoT), which includes networks of related devices that share information and sensors that can collect data on the environment, plants or livestock to inform farming decisions. A range of automation technologies are also being deployed to complete manual, repetitive farming tasks that are either time-consuming or physically challenging for human workers. These include robotic technologies, autonomous vehicles (e.g. driverless tractors) and drones, which can be underpinned by AI to enhance the complexity of tasks that can be completed.

Sensor and automation technologies present opportunities to boost the productivity of Queensland's agriculture industry. In particular, experts consulted in this project saw the potential for low-cost sensors and autonomous systems to reduce the risk for smaller-scale farms in investing in new technologies. They also saw the opportunity for firms providing AgTech advisory services to assist farmers in implementing and integrating various off-the-shelf technologies on their farms. The state's natural strengths in its climate, landmass, proximity to Asia and a long history of agricultural production and expertise provide the necessary building blocks for developing these opportunities for both local and international markets. As these technologies develop and as costs continue to decline in the future, they can be used for more sophisticated agricultural applications. Queensland has a wide portfolio of innovative agricultural research institutes, centres and groups, some of which have been successful in spinning out digital agriculture companies. The state also has the space and the facilities to test and develop these technologies, providing new avenues for attraction in developing this industry opportunity.

2019	2030
155 businesses	**765** businesses
736 direct FTE jobs	**3,637** direct FTE jobs
2,224 indirect FTE jobs	**10,984** indirect FTE jobs

There were 155 agricultural sensor and automation businesses in Queensland as at 30 June 2019 and this is projected to increase to 765 by 2030 (see Figure 16). These reflect firms that directly form part of the agricultural sensor and automation industry, acknowledging that there will be other firms that form part of this industry's value chain. These businesses are estimated to account for 736 direct FTE jobs and 2,224 indirect FTE jobs currently for Queensland and this is predicted to increase to 3,637 direct and 10,984 indirect FTE jobs by 2030 (see Figure 16). These projections are based on the estimated adjusted average annual growth rate of 14% over the next 10 years. To illustrate the potential growth of this sector based on current global growth rates, the number of firms and jobs were forecast using insights derived from published global growth estimates from a comparable or related sector. In this case it was the precision-farming market – enabled by sensor and automation technologies and data analytics – which is predicted to grow at a compound average annual growth rate of 13% from 2020 to 2027.[237] As shown in Figure 16, the projections based on global growth figures show a similar pattern to current trends based on Queensland historical data.

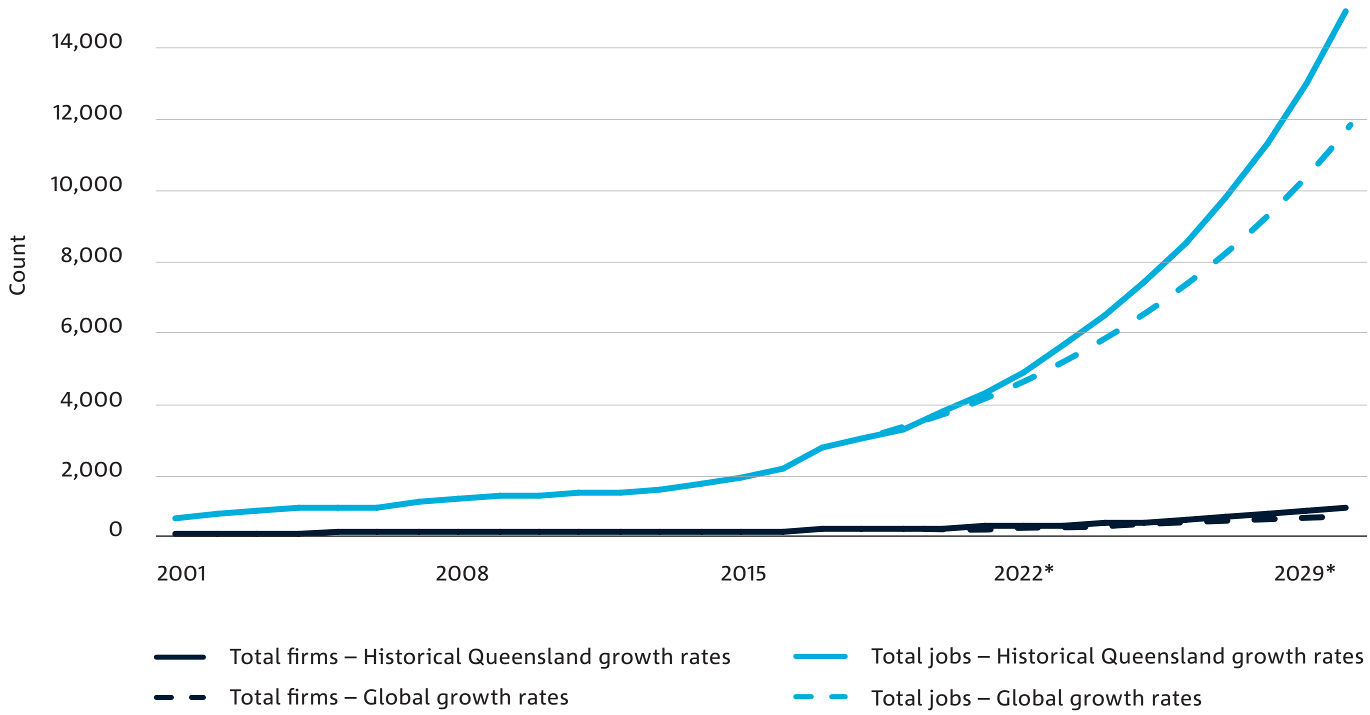


Figure 16. Historical and projected (based on historical Queensland growth rate and global growth rate) number of GST-registered firms and total full-time equivalent jobs (including direct and indirect jobs) in the agricultural sensors and automation industry in Queensland

Note. Years denoted by an asterisk (*) reflect forecasted years.

Why Queensland?

QUEENSLAND'S POTENTIAL AGRICULTURAL SENSORS AND AUTOMATION INDUSTRY AT A GLANCE	
Demand drivers	• Opportunities to boost the sluggish productivity growth of the agriculture sector using digital technologies • A growing movement across Australian agricultural producers to reduce their emissions, optimise resource use and minimise harmful impacts • Using automated technologies to fill labour shortages in the agriculture sector, which have been exacerbated by COVID-19-related international travel restrictions
Supply drivers	• A rich research and development base for digital agriculture, with active portfolios across QUT, Griffith University, JCU, CQU, USQ and UQ • Home to world-leading robotic research groups (QUT and CSIRO's Data61), which act as an enabler for agricultural automation • Access to large, sparsely populated landmass with diverse landscapes and state-of-the-art facilities for testing agricultural technologies • An existing network of agricultural sensors and automation companies, including SwarmFarm Robotics, John Deere Limited, RapidAIM and LYRO Robotics
Challenges and future opportunities	• A small local market with bigger prospects internationally, yet local companies need support in developing export-focused strategies to be competitive • Poor digital literacy and connectivity present persisting barriers to adoption, but these can be addressed through smaller-scale local connectivity solutions • Linking researchers with industry and innovations with farmers to improve adoption through demonstration sites and platform solutions like 'AgTech Finder' • Private investment in AgTech in Australia is lagging behind other countries and companies need stronger economic evidence to invest in the future

Demand drivers

Sluggish agriculture sector productivity growth. Queensland is a key contributor to the national agriculture sector, generating $12.9 billion in the gross value of production and making up 21.4% of Australia's total value in agricultural production in 2018–19.[238] Although demand for food has been increasing and this trend is predicted to continue in line with global population growth,[5,239] productivity growth in the agriculture sector has been variable over the past decade and has begun to decline in recent years relative to the rest of the economy (see Figure 17). The national implementation of digital agriculture is estimated to increase the gross value of agricultural production by $20.3 billion (a 25% increase from 2014–15 levels),[240] with other estimates suggesting that the Australian agriculture sector could be valued at $100 billion by 2030, driven by strong global investment in agricultural technologies.[241] An example area ripe for automation identified by experts is phenotyping in advanced breeding programs – a process which is commonly labour and time intensive.[242] Despite the potential, the Australian agriculture industry has low levels of digital maturity and is missing out on these potential productivity gains.[240] To help drive widespread uptake of digital technologies across agriculture, forestry and fisheries industries, the Australian Government plans to develop a Digital Foundations in Agriculture Strategy.[243]

Desire to reduce the environmental footprint of the agriculture sector. The agriculture industry is vulnerable to changing weather patterns and temperatures. In response to the sector's climate vulnerability, the National Farmers' Federation has advocated for reducing emissions in the agriculture sector and set a target for zero-net emissions by 2050.[245] A growing number of Australian agriculture producers have also committed to carbon-neutral targets, including Arcadian Organic & Natural's Meat Company, Five Founders, Flinders + Co, Talaheni, Jigsaw, Ross Hill, Tulloch and Tahbilk.[246] Digital technologies are providing opportunities for the agriculture sector to reduce its environmental footprint and respond to climate pressures. Examples include CSIRO's 1622 Water Quality online tool, which uses real-time data collected from sensors in waterways and coastal catchments to help sugarcane farmers in Far North Queensland better manage fertiliser use and nitrogen run-off into the Great Barrier Reef.[247] Protected cropping (growing of crops within, under or sheltered by artificial structures) is also augmenting traditional farming methods, given its ability to control the crop environment, optimise resource use and minimise harmful environmental impacts.[248] Automated technologies are being applied in protected cropping, with the Gold Coast firm Stacked Farms developing Australia's first fully automated protected farm for salad greens and herbs.[249]

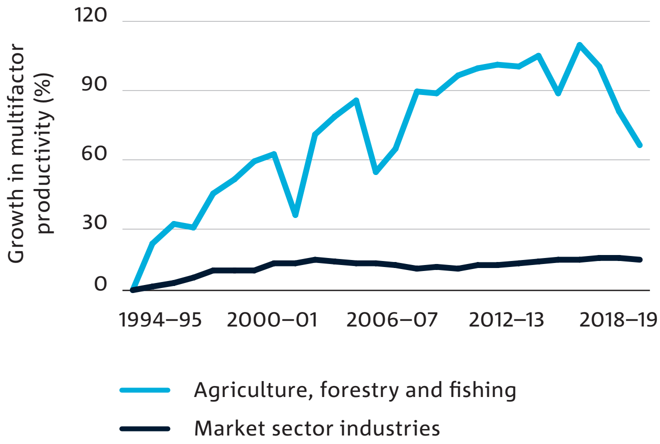


Figure 17. Growth in multifactor productivity in agriculture, forestry and fishing and across all market sectors in Australia (index, 1994–95 = 100)

Data source: Australian Bureau of Statistics[244]

Note. 'Market sector industries' include all sectors classified under the Australian and New Zealand Standard Industrial Classification.

Agricultural labour shortages intensified by global pandemic. The agriculture sector faces a number of workforce challenges. First, the agriculture workforce is ageing, with the average Queensland farmer aged 57.9 years in 2018–19 – an increase from 56.6 years in 2013–14.[210,250] This is a symptom of the sector's struggle when it comes to sourcing new skilled workers. Agriculture, environmental and related studies consistently attracts the lowest share of persons studying towards a post-school qualification and this share has been in decline over the past decade (see Figure 18). Agricultural sectors like the horticulture sector rely heavily on seasonal labour, with the bulk of these workers being temporary visa holders.[251] The usual supply of backpackers and other foreign workers has been disrupted by the global COVID-19 pandemic, with restrictions limiting international travel.[252] Ernest and Young estimate that the Australian agriculture industry will be up to 26,000 workers short by March 2021,[253] and this impact could be greater given that international travel restrictions are expected to persist through 2021.[254] These labour shortages could be a strong driver and catalyst for automation, where robots and other technologies could substitute for seasonal and low-skilled labour[255] or assist existing workers to improve their productivity. Moreover, technology adoption in agriculture could assist the sector in shifting out-dated public perceptions around a career in agriculture and attracting future knowledge workers looking for technology-intensive careers.

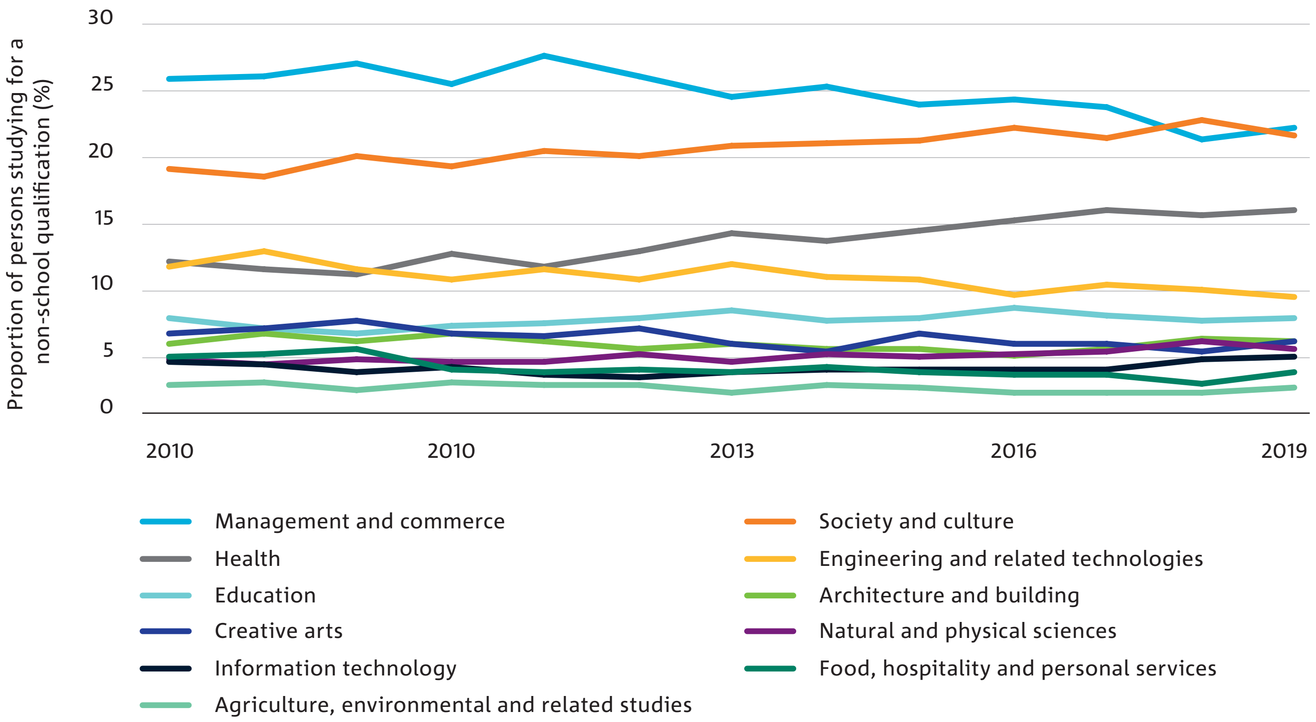


Figure 18. Proportion of persons studying a non-school qualification by main field of study

Data source: Australian Bureau of Statistics[256]

Supply drivers

Queensland universities driving digital agriculture innovation. Queensland's universities have deep expertise in a diverse range of digital agricultural domains. QUT's Future Farming group and the Centre for Robotics have developed a large portfolio of automated agriculture technologies for tracking and monitoring crops and improving efficiencies on the farm.[257] Griffith University is using AI to automate quality monitoring in horticulture.[258] JCU is home to the Agriculture Technology and Adoption Centre, which develops industry-driven agriculture technology solutions using AI, data science, sensor networks and advanced manufacturing.[259] Central Queensland University's (CQU) Institute for Future Farming Systems focuses on precision agriculture technologies, including the development of non-invasive sensor platforms for monitoring and tracking individual animals (e.g. DataMuster).[260] USQ's Centre for Agricultural Engineering is leading research into the use of sensors, robotic and computing technologies in driverless tractor technologies and other forms of machine automation and control.[261] Finally, research at UQ's Queensland Alliance for Agriculture and Food Innovation (QAAFI) covers a diverse range of digital agriculture areas, including sensors, automation, crop modelling and forecasting, and has developed a remote-sensing tractor that collects data on crop performance to identify the optimal genotype.[262]

Strength in robotics research opens up agricultural opportunities. Agriculture is one of the many areas where Queensland researchers have been applying robotics. For example, QUT's Centre for Robotics has developed a robotic vegetable harvester (nicknamed 'Harvey') and autonomous weed and crop management machinery for broadacre farming (AgBot II), both of which have been significantly co-funded by the Queensland Government.[257] These draw upon QUT's world-leading strengths in robotic vision housed in the Australian Centre for Robotic Vision.[263] CSIRO Data61's Robotics and Autonomous Systems Group is also a world leader in robotics research, specialising in field robotics, autonomous vehicles and wireless technologies for a broad range of industries.[264] Relevant agricultural examples include the ResQu project, in which unmanned helicopters were developed in collaboration with Biosecurity Queensland to map weeds in difficult terrain; world-leading technologies in virtual fencing; and AgScan3D+, a sophisticated sensor technology that can be retrofitted to a farm vehicle to measure the health, structure and quality of crops.[265] Although other Australian states have strong robotics capabilities too, Brisbane's reputation as a world-leading robotics hub is growing, with the city hosting the first International Conference on Robotics and Automation in the southern hemisphere in 2018,[266] and the World of Drones Congress on an annual basis since 2017.[267] Growing Queensland's capabilities in robotics will have benefits for agriculture and flow-on impacts for other emerging industries.

Ideal testbed for agricultural technologies. Queensland has a large landmass, low population density, proximity to Asia and diverse landscapes. These strengths provide fertile grounds for growing a range of crops and livestock that, in turn, can be used to test novel agricultural sensor and automation technologies. Queensland also has excellent testing facilities for agriculture technologies in the pipeline. For example, the Queensland Government plans to establish a $3.3 million AgTech and logistics hub in Toowoomba where agricultural technologies can be developed, built and tested with a view to commercialisation and attracting investment.[268] CQU has also opened an AgTech facility in Bundaberg, which aims to support agricultural research and development in the region and the translation and commercialisation of agricultural innovations.[269] Other enabling facilities include the Robotics Innovation Centre hosted by CSIRO Data61's Robotics and Autonomous Systems Group,[270] and the Australian-first testing facility for small-to-medium-sized drones planned for construction in Cloncurry, Queensland.[271] These facilities not only support Queensland researchers and companies to develop technologies for agriculture and other applications, but could also be attractive for international companies.

Growing network of agricultural sensor and automation technology companies. SwarmFarm Robotics is a Central Queensland-based company that focuses on the deployment of smaller, more cost-effective 'swarms' of autonomous machines.[272] These types of lower-cost autonomous systems may be particularly attractive to innovation-active agriculture businesses, who have identified access to funding and the cost of development or implementation as the top barriers to innovation.[273] Ceres Tag is another Queensland-based company that has developed, in collaboration with JCU and CSIRO, a smart ear tag for cattle to monitor their location, health and welfare.[274] John Deere Limited, a leading provider of agricultural machinery and equipment, has a long-standing research innovation partnership with USQ.[275] Queensland also has several successful AgTech start-ups that come from the Queensland research sector. Examples include RapidAIM, an insect monitoring technology company that spun out of CSIRO's Data61 which uses IoT technologies to detect fruit flies in crops in real-time.[276] LYRO Robotics is a spin-out from the Australian Centre for Robotic Vision that specialises in picking and packing agricultural and logistics robots[277] This business base provides strong foundations for future growth and development in this industry.

Challenges and future opportunities

Selling to a small local market and competing globally. Experts commented that the market for agricultural sensors and automation is small in Australia. Cost can be a significant limiting factor in implementing sensor or robotic technologies, especially given it can take years to accumulate useful data for accurate decision making and the return on this investment may not be apparent in the short term.[255] The Australian agribusiness ecosystem also lacks large, globally renowned businesses that can support the industry in competing internationally.[278] Global competition for agriculture technologies is significant and countries like Israel, the United States and the United Kingdom have already established strong AgTech ecosystems.[241] Experts consulted in the project felt there could be novel market opportunities for researchers and companies to develop low-cost sensor and robotic systems that present a lower investment risk for smaller farms. Moreover, experts suggested that policy support and incentives could be provided to international companies to establish their research and development faculties in Queensland, providing an incubator for developing globally relevant solutions.

Addressing connectivity barriers on farms and poor data infrastructure. Poor digital literacy is a persisting challenge across agricultural value chains that limits the adoption of digital agriculture solutions.[240] Experts consulted in this report felt agricultural workers often lack the digital literacy to use sensor and automation technologies and analyse the resulting data, and conversely, technology developers lack domain expertise. Skill-development programs are needed to support the translation of digital agriculture solutions from the lab to the farm. Digital connectivity is another barrier to adoption in rural and remote areas. Although the digital divide between urban and rural areas has been improving, Brisbane still scores higher in measures of digital access (77.9 out of 100) compared with rural Queensland (72.8).[279] Connectivity barriers not only impact the future growth of the agricultural sensors and automation industry, but also any knowledge-driven sector that has a strong regional basis (e.g. supply chain provenance technologies). To address rural connectivity issues on farms, the Western Australian Government funded a $277,500 grant in 2019 to implement 4G mobile technology to connect 50 farms within a 100 km radius, enabling farmers to process data collected from on-farm sensors and remote devices.[280] The Western Australian Government has also invested $582,800 in the WA IoT DecisionAg Grant Program to address issues around on-farm connectivity.[281] Queensland could explore similar mechanisms for supporting Queensland farmers in overcoming connectivity issues and trialling on-farm sensor and automation technologies.

Building a bridge between solutions and farmers. Previous work by StartupAUS, KPMG, the Queensland Government and the Commonwealth Bank found that Australian farmers would benefit from greater visibility of the available solutions and vendors.[241] The commercialisation pathways associated with AgTech can be complex and stakeholders consulted in this project noted that products tend to be technology-driven rather than end-user driven and the need for researchers and developers to engage their end-users when developing digital agriculture solutions. To improve the connectivity between researchers, developers and industry, KPMG, in collaboration with the Food Agility CRC and other industry groups, has developed an online marketplace for agricultural technologies called 'AgTech Finder'.[282] This platform aims to connect Australian farmers with a technology solution based on their needs and problems, as well as build awareness around what is available in the market.[282] In partnership with the Food Agility CRC, the Queensland Government has built a state-based portal to connect agribusinesses to the growing AgTech ecosystem in Queensland.[283] The Queensland Government has also established 'Smart Farm' industry demonstration sites at the Gatton Research Facility to improve technology adoption and adaptation in agribusinesses. Experts suggested there could also be novel service sector opportunities in AgTech, wherein skilled workers who possess both technical and agricultural domain knowledge could support farmers in implementing technologies on the farm and integrating them in a connected platform.

Increasing the level of private investment in AgTech. The Queensland Government will invest $3.3 million in the AgTech and logistics hub planned for Toowoomba,[268] in addition to the $14.5 million drone testing facility for Cloncurry.[271] The Australian Government has invested $150 million into the Food Agility CRC, which is researching agricultural sensor and computing technologies.[284] The Australian Government has also invested $5 billion through its Future Drought Fund, $86 million of which will go towards eight Drought Resilience Adoption and Innovation Hubs to support research, development and innovation around drought resilience.[285] However, private investment in agricultural technologies is lacking in Australia, with the total venture capital investment in Australian AgTech ($5.9 million in 2017) equivalent to the average of a single early-stage venture capital deal in the United States ($5.7 million in 2016).[286] One contributing factor to the current low levels of private investment in AgTech could centre around the challenges that researchers and technology companies face in providing the evidence and data on the economic and non-economic benefits provided by technology. To help build this evidence base, the government could focus its funding efforts on research projects that aim to demonstrate the future viability or scalability of AgTech innovations to strengthen investor confidence.

Related industry opportunity areas

- **Resource recovery technologies:** using these technologies to monitor and collect agricultural waste, which can be used to produce new high-value products (e.g. biofuels)
- **Supply chain provenance technologies:** common technologies applied across these sectors and opportunities to link data collected on the farm and across food supply chains
- **Agriculture and aquaculture:** key consumers of sensor and automation technologies, which are designed to create efficiencies and productivity gains in these traditional sectors
- **Protected cropping:** an area of application for sensor and automation technologies to improve high-value horticulture yields in protected environments
- **Advanced manufacturing:** the need for capabilities in advanced manufacturing to transition digital agriculture innovations from prototype to the market

7 Supply chain provenance technologies

Australia has a strong international brand, with a reputation for safe, high-quality food and agricultural exports. However, this strong reputation is increasingly being put at risk by food fraud in our key export markets. Supply chain provenance technologies can be used to track and trace food products along the entire value chain, from the paddock or the farm to the consumer. These technologies enhance the transparency of the entire supply chain, providing producers, wholesalers, freight and logistics operators, retailers and consumers with oversight over product transactions. While Queensland research into supply chain provenance technologies has focused on blockchain technology and the IoT to date, other technologies include traceable markers, genetic testing, remote surveillance systems, image recognition and other automated monitoring systems. The provenance story associated with food products can be communicated to consumers via these technologies, adding value by conveying the authenticity, origin and other commercially relevant information (e.g. ethical practices).

Enhancing the traceability systems associated with Queensland's domestic and export markets will serve to protect the value-added attributes associated with Australian products, maintain and build trust amongst consumers and potentially ease the regulations associated with importing Australian products into other countries. There may also be opportunities for these systems to support a two-way flow of information, enabling producers to learn more about their consumers and markets for their products. While Queensland's research and commercial applications for supply chain provenance technologies have focused on food and agricultural markets to date, these technologies are increasingly being applied to track the end-to-end lifespan of recyclable materials. Using supply chain provenance technologies to improve the transparency of recycling processes can help build and maintain the community's trust in these processes. Queensland has an emerging base of researchers and firms using cutting-edge technologies and approaches to improve the traceability of its supply chains and this is an area that is gaining significant government and private-sector investment.

	2019	2030
	107 businesses	**546** businesses
	508 direct FTE jobs **79** indirect FTE jobs	**2,595** direct FTE jobs **402** indirect FTE jobs

There were 107 supply chain provenance technology businesses in Queensland as at 30 June 2019 and this is projected to increase to 546 by 2030 (see Figure 19). These reflect firms that directly form part of the supply chain provenance technologies industry, acknowledging that there will be other firms that form part of this industry's value chain. These businesses are estimated to account for 508 direct FTE jobs and 79 indirect FTE jobs for Queensland currently and this is predicted to increase to 2,595 direct and 402 indirect FTE jobs by 2030 (see Figure 19). These projections are based on the adjusted 10-year average annual growth rate of 14.3%. To illustrate the potential growth of this sector based on current global growth rates, the number of firms and jobs were also forecast using insights derived from published global growth estimates from a comparable or related sector. The global blockchain in supply chain market is forecast to grow at an average annual rate of approximately 60% between 2019 and 2025,[287] with the blockchain market for agriculture and food supply chains specifically predicted to grow by 48.1% per year from 2020 to 2025.[288] The average of these two estimates was used as the global growth rate estimate. As shown in Figure 19, Queensland could experience much greater growth in this sector if the rate of change increases in line with global trends.

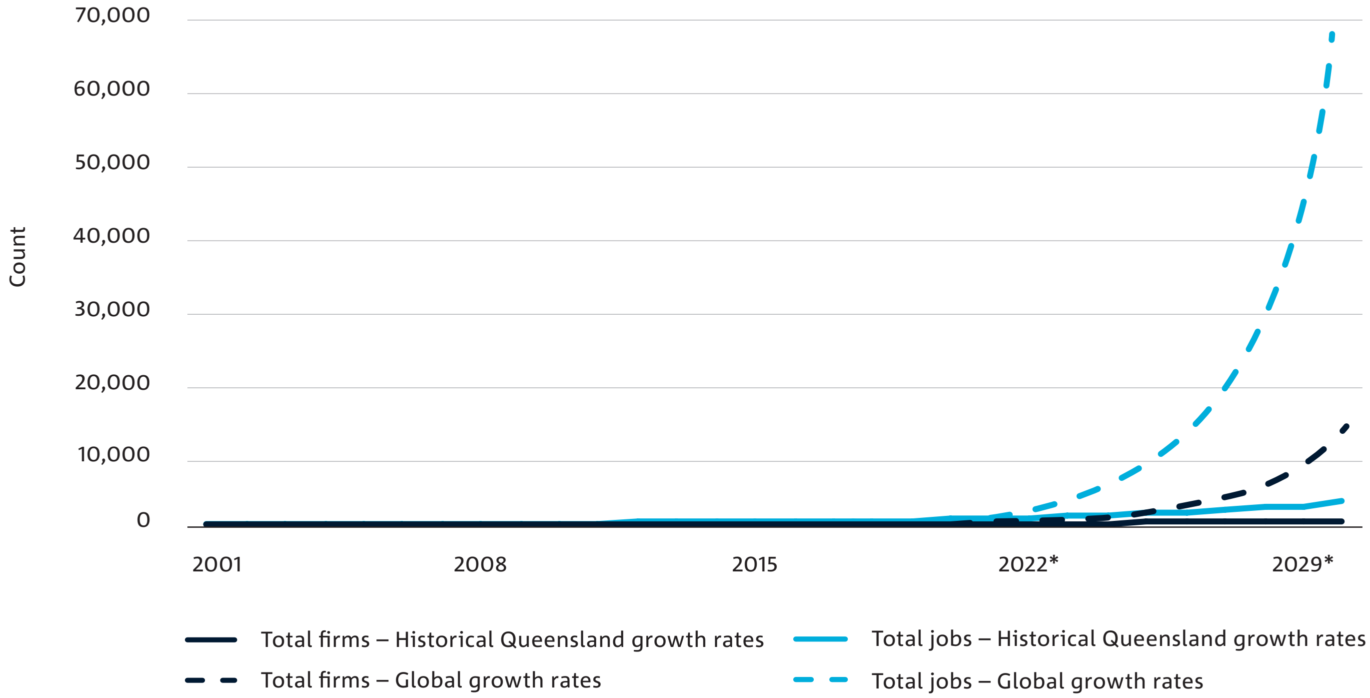


Figure 19. Historical and projected (based on historical Queensland growth rate and global growth rate) number of GST-registered firms and total full-time equivalent jobs (including direct and indirect jobs) in the supply chain provenance technologies industry in Queensland

Note. Years denoted by an asterisk (*) reflect forecasted years.

Why Queensland?

QUEENSLAND'S POTENTIAL SUPPLY CHAIN PROVENANCE TECHNOLOGIES INDUSTRY AT A GLANCE	
Demand drivers	• High costs of counterfeit products and the vulnerability of Australian suppliers to food fraud due to their reputation for safe and quality food and wine exports • Opportunities to use technologies to verify the provenance and authenticity of Australian food exports in increasingly competitive Asian markets that are demanding higher-value food products • Consumers want greater transparency around their food products following a series of high-profile food fraud incidents
Supply drivers	• State and federal government investments in traceability systems to improve the transparency of agricultural supply chains and safeguard the reputation of Australian producers • Existing research programs on food provenance, including QUT's collaboration with BeefLedger and research conducted at JCU, CSIRO and UQ • Local companies already working to improve the traceability of Queensland supply chains, such as BeefLedger and AgriChain for food exports and EverLedger for recycled materials
Challenges and future opportunities	• The need for a dedicated collaborate research initiative that brings together the state's diverse capabilities around food provenance and supporting technologies • Ensuring funding for basic research into supply chain provenance is prioritised alongside applied research and experimental development activities • Creating novel job creation opportunities in regional Australia by engaging communities in the development of local food provenance stories • Local and global markets for supply chain provenance technologies are currently small, but are likely to grow given the economic impacts of counterfeiting incidents

Demand drivers

Costly fight against counterfeit products. Food fraud is a significant global issue, costing $50 billion each year.[289] It is also a challenge for Australia's food and wine exports, costing the sector approximately $1.7 billion in 2017, with dairy, wine and meat bearing the largest share of food fraud costs.[289] Given its strong reputation for safe, quality food and wine exports, Australian suppliers are prime targets,[290] and this trend has worsened as Australian exports to countries with a high risk of food fraud have increased.[289] At least 50% of Australian wines are substituted with counterfeit products in Asia, with popular, high-end brands like Penfolds often substituted for 'Benfolds'.[290] Australian companies, such as the vitamin group, Blackmores, in collaboration with Alibaba, are trialling the use of supply chain provenance technologies (e.g. blockchain) to track and monitor goods imported into Asia to curb the sale of fraudulent products.[291] Supply chain provenance technologies provide a means for protecting Australia's 'clean, green and secure' reputation and offer assurance to customers and importing countries that the Australian food and wine products they purchase adhere to strict food safety standards.

Rising demand for higher-value food exports to Asia. The global middle-class population was 3.2 billion in 2016 and this is expected to increase to 5.2 billion by 2028, with around 88% of new entrants to the middle-class residing in Asia.[292] As a result, demand for higher-value food products has been increasing, with the average person in Asia consuming a similar amount of protein per day (77.6 g) as the global average (81.2 g, 2013 figures).[293] Asian consumers view beef as a superior source of protein and the amount of beef imported into China each year has been growing exponentially over the past decade in response to increasing demand.[240] Queensland is the largest exporter of red meat in Australia, accounting for 39% of the country's total red meat exports in 2018–19.[294] With food fraud becoming an increasing issue for Australian food exports (see *The costly fight against counterfeit products* driver above), and with competition for Asian beef markets increasing,[295] verifying the provenance and authenticity of Queensland beef and other food exports will be critical in maintaining the sector's brand, reputation and competitive advantage.

Consumer demand for greater transparency around food products. Asian consumers have experienced a series of high-profile food fraud incidents in the past, including the contamination of infant formula with melamine,[296] out-of-date meat sold in fast food retailers[297] and the use of recycled waste oil in food production.[298] UK consumers' trust has similarly been tested after traces of horsemeat was found in burger patties sold in supermarkets.[299] Food fraud damages consumers' confidence and trust in the authenticity, quality and reliability of food products from local and international supply chains.[300,301] Blockchain and other supply chain provenance technologies and approaches could be used to improve the transparency around food and other consumer products, and this demand is likely to be greatest in countries where there is a high risk of fraudulent food products. A recent survey found that while most Chinese consumers are not familiar with how blockchain technologies can be used to authenticate food supply chains (87.4%), 99.1% would be more likely to purchase blockchain-verified lamb over an unverified product if they were equal in price.[302] Over half of consumers (51%) would be willing to pay 5–15% more for blockchain-verified products.[302] It is unclear at this stage, however, how much it would cost industry to implement a blockchain-verified system and what the resulting price would be for consumers.

Supply drivers

Government investment for improving Australia's traceability systems. In 2019, the Australian Government established the National Traceability Framework, which aims to provide a guide for industry and government to enhance the traceability systems associated with food and agricultural exports.[303] To support the industry in implementing food traceability systems, Deakin University's Centre for Supply Chain and Logistics, in collaboration with industry partners, has developed an Australian-first guide for tracking and tracing food products across the supply chain for domestic and international markets.[304] Moreover, the Australian Government has committed $7 million as part of its Traceability Grants Program, which will run from 2019–23.[305] Queensland-based firm, Honey and Fox, was a successful recipient under this funding program and plans to develop an interactive decision-support tool to help producers identify traceability systems based on their business needs.[305,306] The Queensland Government has also announced a $5.5 million investment to improve the traceability, biosecurity and food safety of agricultural supply chains.[307] With importing countries imposing stricter regulations around food safety, investment in enhancing Australia's traceability systems will assist producers in maintaining and expanding their export markets in the future.

Research capabilities in tracking and tracing provenance. QUT, in collaboration with BeefLedger – a Queensland-based beef export provenance technology company – is using blockchain and IoT technologies to create a platform for tracking and tracing Australian beef exports,[308] which are highly susceptible to food fraud.[309] T-Provenance, an Adelaide-based CSIRO spin-out, is using blockchain and IoT to enhance the authenticity and traceability in Australian food industries,[310] including mangos in North Queensland.[311] QUT is also embarking on new research that aims to provide a 'DNA' stamp for plastics in the circular economy.[312] JCU, in collaboration with CSIRO, has also developed the Digital Homestead, a decision-making platform that combines data from on-farm and remote sensors and other data sources, to explore potential 'paddock to plate' applications for beef supply chains.[313] JCU and QUT are also partners in the Food Agility CRC, which covers research into tracking and traceability systems for seafood and red meat markets.[284] Researchers at UQ's QAAFI are also conducting research to understand the provenance signature of uniquely Australian food products,[314] which could be communicated to consumers and authenticated using supply chain provenance technologies and platforms.[315] Other supply chain provenance technologies include traceable markers and biomarkers.[290] These technologies will become more sophisticated as supporting technologies, like cloud computing, IoT, blockchain, quantum computing and AI, develop.

Local firms working to improve Queensland supply chains. There is an emerging cluster of Queensland firms applying supply chain provenance technologies for agribusinesses, including the aforementioned BeefLedger, which has collaborated with QUT on a range of beef provenance projects.[316] BeefLedger is also collaborating with CSIRO's Data61 in a trial to improve the cost and ecological effectiveness of its remote sensors.[317] Others include the Sunshine Coast-based company, AgriChain, which uses blockchain technologies to track and transfer information between providers, supporting end-to-end visibility across the entire agricultural supply chain.[318] AgriChain has recently received $6 million in venture capital funding.[319] EverLedger, a London-based technology company which uses a range of provenance technologies to track asset information, has also partnered with Griffith University in a program of work that aims to apply traceability systems to track materials (e.g. tyres) across their lifespan to inform future waste management initiatives.[320] EverLedger, in collaboration with the Circular Economy Lab and other industry partners, is also using blockchain technology to track and trace upcycling processes associated with recycled materials to restore social trust.[321]

Challenges and future opportunities

Coordinating supply chain provenance technologies research. Queensland has a diverse range of research institutions and groups that are actively conducting relevant food and waste provenance research, but experts commented that these research streams are siloed with limited connectivity. There is a need to improve the coordination of these research activities. The establishment of the Food Agility CRC and Food Systems CRC have helped bring together national research, industry and government capabilities in a broad range of areas focused on improving the productivity, sustainability and global competitiveness of the Australian agrifood sector. However, there is no dedicated CRC or other collaborative research initiatives for supply chain provenance technologies. By bringing together Queensland's capabilities in food provenance knowledge and technologies, the state will be in a better position to understand the system needed to provide the trust, authenticity and storytelling associated with local food and non-food exports. This will enhance the value of these products and provide novel insights into the economics behind these systems and target consumer markets.

Funding to support a long-term vision. Experts believed more basic research is needed to better understand the fundamental systemic change needed to improve the provenance traceability of food and other exports. At present, there is limited empirical evidence to demonstrate the feasibility and scalability of provenance-related blockchain trials to provide investor confidence in these technologies. A previous cost-benefit analysis on food fraud estimated $2.52 million would be needed annually over a 10-year period for food-fraud-related research activities to build the technological capabilities needed to detect food inauthenticity and insure the Australian brand.[289] Current funding initiatives tend to be short-term focused and project-specific, rather than reflecting a broader long-term vision and research portfolio for supply chain provenance. While there have been recent industry-focused investments from state and federal governments,[305,307] these investments may not improve basic knowledge around the authenticity and traceability of Queensland's supply chains if the funding is prioritised towards applied research and experimental development activities.

Engaging regions in telling provenance stories. The supply chain provenance technologies industry has the potential to open up new job creation opportunities for regional areas in Queensland. This has been demonstrated through QUT's work with BeefLedger, where they engaged the South Australian District Council of Grant community and Mount Gambier High School students to co-develop local content that could be used in telling food provenance stories about the region's Limestone Coast beef.[322] Storytelling is a key component of communicating the brand and provenance associated with consumer products and building consumer trust.[315] Growth in supply chain provenance technologies could strengthen demand for professional cultural intermediaries in regional locations, which could encompass a broad range of roles (e.g. brand managers, curators, social entrepreneurs, community, facilitators, etc.).[322] Traditional knowledge could feature in Australian food provenance stories and the research and training conducted through UQ's ARC Industrial Transformation Training Centre for Uniquely Australian Foods could support industry leaders in promoting sustainable and culturally appropriate applications of native foods.[314] These job opportunities demonstrate the importance of both technical data and digital skills, along with 'softer' skills in community engagement and digital marketing in supporting the growth of this industry.

Growing the global market for supply chain provenance technologies. Analysis by BIS Research suggests that the global blockchain in agriculture and food market was valued at $56.7 million in 2018 and this is expected to grow to $1.9 billion by 2028.[323] Compared with the size of global markets for the other seed industries discussed in this report (e.g. the digital health market, valued at $678 billion by 2027[80]), the global market for supply chain provenance technologies is predicted to be comparatively smaller. This could present a challenge for local Queensland companies while demand is still developing. The drivers highlighted for this industry, however, provide strong signals that demand will grow. For example, the economic impact of food fraud and counterfeit products is significant for Australian producers and supply chain provenance technologies could mitigate this impact. Moreover, consumer demand for transparency around their food products is increasing, particularly in Asian countries where several high-profile food fraud and counterfeiting incidents have occurred,[296–298] and where concerns around trace elements of metals in seafood exports have recently halted trade with Australia.[324] Incidents like these will likely drive industry, including Australian producers, to develop ways of improving the transparency of their supply chain.

Related industry opportunity areas

- **Agricultural sensors and automation:** common technologies applied across both sectors and the opportunities to link data collected on the farm and across food supply chains
- **Resource recovery technologies:** opportunities to use supply chain technologies to track the end-to-end lifespan of recyclable materials
- **Agriculture and aquaculture:** potential users of supply chain technologies to enhance the value of food products, protect against food fraud and provide producers with insights into their markets
- **Transport and logistics:** the ability to use supply chain technologies as part of existing transport and logistics networks to track and trace transactions from the farm to the consumer
- **Wholesale and retail:** opportunities to enhance the transparency of wholesale and retail transactions through the use of supply chain technologies
- **Mining and resources:** translation opportunities for the mining and resources sector to repurpose technologies developed for tracking agricultural and waste for resource supply chains
- **Waste management, treatment, and remediation:** supporting the management of recyclable materials by using supply chain technologies to track the end-to-end lifespan of these materials
- **Advanced manufacturing:** drawing upon advanced manufacturing capabilities to develop the technologies needed to support this industry

8 Disaster resilience and response technologies

Disaster resilience focuses on understanding and forecasting the impact of natural hazards and mitigating their impacts on communities. Queensland is the most disaster-prone state in Australia and these impacts are predicted to worsen as natural hazard events become more frequent due to climate change.[325] Digital technologies provide new avenues for pre-empting, responding and recovering from a disaster event. For example, robots can assist humans in performing challenging tasks in a disaster, improving the safety and efficiency of disaster responses.[326] During or following a disaster event, drones could be used to capture images on properties and AI could be applied to compare these images with previous images to determine the extent of the damage. Insurance companies could use this information to verify damages, speeding up recovery times for individuals and companies and providing assurances for insurance companies. Machine learning could also be used to analyse and predict the occurrence of and response to natural hazards.[326]

The increasing frequency and intensity of natural hazards and their associated economic costs highlight the importance of investing in this seed industry.[327] Advancements made in Queensland can and should be translated across Australia and internationally, supporting other jurisdictions in responding to the social, economic and environmental impacts of wildfires, droughts, heatwaves, floods, cyclones and other natural hazards. This presents an opportunity for Queensland to export these solutions to other countries experiencing similar challenges . Queensland's research expertise not only covers disaster resilience and natural hazards, but the state also has strong complementary capabilities in robotics and environmental modelling. South-East Queensland is also home of a growing network of start-ups actively working to develop and apply technologies in this space. Fuelled by the 2019–20 Black Summer bushfire season and the 2011 Brisbane floods, disaster resilience is an area that is attracting significant public and private investment.

2019	2030
365 businesses	**927** businesses
1,693 direct FTE jobs	**4,298** direct FTE jobs
1,314 indirect FTE jobs	**3,335** indirect FTE jobs

There were 365 disaster resilience and response technology businesses in Queensland as at 30 June 2019 and this is projected to increase to 927 by 2030 (see Figure 20). These reflect firms that directly form part of the disaster resilience and response technologies industry, acknowledging that there will be other firms that form part of this new industry value chain, which also create economic and employment opportunities. These businesses are estimated to have created 1,693 direct FTE jobs and 1,314 indirect FTE jobs for Queensland currently and this is estimated to increase to 4,298 direct and 3,335 indirect FTE jobs by 2030 (see Figure 20). These projections are based on the estimated adjusted average annual growth rate of 7.9% over the next 10 years. To illustrate the potential growth of this sector based on current global growth rates, the number of firms and jobs were forecast using insights derived from published global growth estimates from a comparable or related sector. For this sector, the global incident and emergency management market, which is expected to grow by an average annual rate of 5.9% from 2020 to 2024,[328] was used as an index of the potential global growth rate.

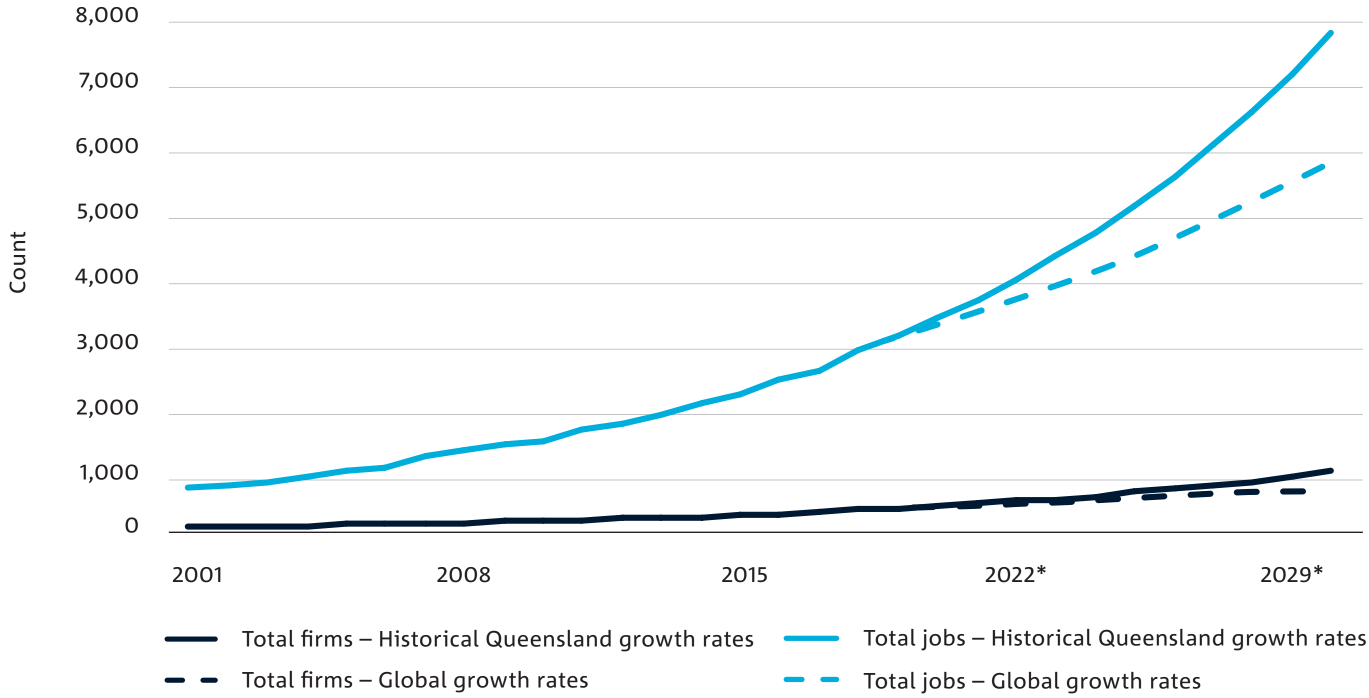


Figure 20. Historical and projected (based on historical Queensland growth rate and global growth rate) number of GST-registered firms and total full-time equivalent jobs (including direct and indirect jobs) in the disaster resilience and response technologies industry in Queensland

Note. Years denoted by an asterisk (*) reflect forecasted years.

Why Queensland?

QUEENSLAND'S POTENTIAL DISASTER RESILIENCE AND RESPONSE TECHNOLOGIES INDUSTRY AT A GLANCE	
Demand drivers	• Natural disasters are costly for Queensland and Australia, as well as other countries such as China, the United States and developing countries • Natural hazards have a significant environmental burden (e.g. landmass destroyed, emissions generated) and social burden (e.g. lives lost, long-term mental health impacts) • The need to protect the future livelihoods of Queensland industries that are vulnerable to variable weather patterns (e.g. agriculture, retail, tourism) • Opportunities to improve the safety outcomes for humans in responding to disaster events using robots and autonomous systems
Supply drivers	• Existing expertise and research capabilities in disaster risk reduction, resilience and post-disaster response and recovery, covering JCU, CQU, QUT, USQ and UQ • Opportunities to draw upon local strengths in robotics to develop innovative disaster technologies, such as the OzBot Titan firefighting robot, the Hovermap inspection and mapping drone, and autonomous tree-planting fleets, Growbots • The 2019–20 Black Summer bushfires triggered significant public-sector and private-sector investment in disaster technologies • An emerging cluster of fire-tech start-ups on the Sunshine Coast with links to international companies across Australia, the United States, Canada and Asia
Challenges and future opportunities	• The boundaries of this industry are blurry, but this presents an opportunity to define and set the strategic direction and vision for the industry • Opportunities to repurpose existing robotic and autonomous systems technologies for disaster purposes and an audit of existing innovations could help identify potential opportunity areas • Current gaps in the manufacturing supply chain for robotics, but opportunities to draw upon the state's strong advanced manufacturing network to fill this void • Uncertainty around how growth in the disaster resilience and response technologies sector might impact the insurance sector, with the potential to reduce premiums or drive innovation in insurance products

Demand drivers

Queensland's costly natural disasters. Queensland has the highest rate of natural disasters in Australia,[329] costing the Queensland economy an average of $6.2 billion per year between 2007 to 2016.[330] These costs are predicted to rise to $18 billion per year by 2050.[330] Floods are the most costly natural disaster for Queensland (65% of costs), followed by cyclones (25%). The damage bill is even higher in the United States, China and Japan, with these countries making up almost two-thirds of the total global economic damage caused by natural disasters (see Figure 21). After China and the United States, developing countries also bear a large share of the social impacts of disaster events (e.g. Philippines, India, and Vietnam), even though the economic damage bill is less given the level of development in these countries.[331] The high costs associated with natural hazards signal an imperative for greater preparedness, response and recovery capabilities for natural disasters in Queensland. There is also an opportunity to export these solutions to other jurisdictions with similar challenges.

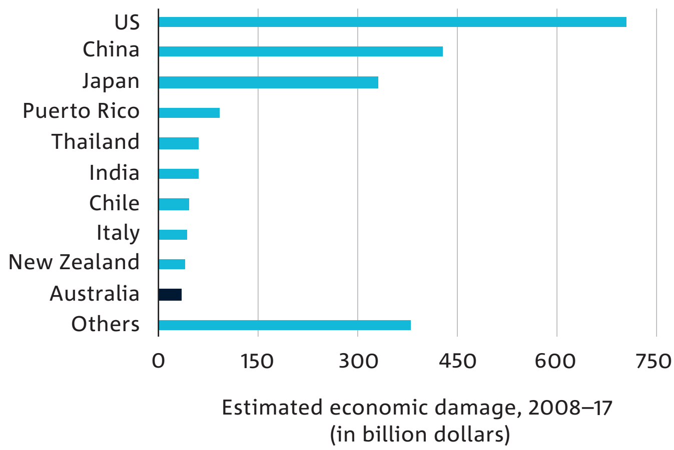


Figure 21. Estimated economic damage of natural disasters across selected jurisdictions, 2008–17

Data source: International Federation of Red Cross and Red Crescent Societies[331]

Social and environmental burdens of natural hazards. While extreme natural disasters can be costly, they also have significant social and environmental impacts. For example, the excessive smoke generated by the Black Summer bushfires of 2019–20 in Australia resulted in 417 excess deaths and 3,151 hospitalisations due to cardiovascular and respiratory problems and an additional 1,305 emergency department presentations for asthma across New South Wales, Queensland, the Australian Capital Territory and Victoria.[332] The fires also burnt approximately 18.9 million ha of land across Australia (2.5 million ha in Queensland),[332] destroyed 3,113 houses (48 in Queensland),[332] killed over 1 billion animals,[332] and generated around 830 million tonnes of CO_2 equivalent.[333] Extreme weather is also a significant psychological stressor: hot days have a similar impact on mental health as unemployment,[334] and extreme weather events like the 2011 Brisbane floods have been associated with long-term heightened levels of psychological distress.[335] Increasingly frequent and severe weather events in Australia could challenge the health and well-being of its communities and the capacity of its environment to regenerate.

Queensland industries vulnerable to variable weather patterns. Primary industries such as agriculture, forestry and fishing as well as retail and tourism are among some of Queensland's most climate-sensitive sectors. These sectors are significant contributors to the Queensland economy, with agriculture generating $12.9 billion in gross value-added production in 2018–19,[238] and rural exports making up 11.2% of Queensland's total exports in 2019–20.[336] Moreover, Queensland's tourism sector contributed a total of $28.3 billion to GSP in 2018–19, making up 7.7% of Queensland's economic activity.[153] Disruptions to these industries as a result of extreme weather or a natural disaster, among other factors, could have a significant impact on the Queensland economy. For example, the 2019–20 Black Summer bushfires were estimated to cost the tourism, retail and agriculture sectors between $2–3 million in lost income and production.[337] Building resilience to natural disasters will be critical in supporting the long-term economic prosperity of Queensland industries.

The need to make disaster preparedness, response and recovery better. Robots or other autonomous systems could substitute for humans in disaster events to reduce health and safety risks. Although pandemics would not be considered natural disasters, there are some parallels that we can draw from using technologies in these events too. In response to the COVID-19 pandemic, researchers from Texas A&M University and the Center for Robot-Assisted Search and Rescue analysed social media reports and identified uses of ground and ariel robots for quarantine enforcement, the disinfection of public and clinical spaces, delivery services and handling of infectious materials.[338] For example, Blue Ocean Robotics have developed ultra-violet disinfection robots (UVD Robots) that can be used to prevent the spread of infections in hospital settings.[339] Robots can also be used in disaster events for tasks that cannot be completed, or completed safely, by a human and to help human workers better manage their increased workload.[338] Compared to humans, robots can also be more efficient, precise and do not experience suffering or tiredness under crisis.

Supply drivers

Deep expertise on natural disasters. Queensland is home to research groups with expertise in disaster risk reduction, resilience and post-disaster response and recovery. For example, JCU's Centre for Disaster Studies researches climate adaptation, disaster risk reduction and management, and post-disaster assessments, with a focus on cyclones.[340] This Centre is also a partner in the Bushfire and Natural Hazards CRC, along with CQU, QUT and USQ, which aims to coordinate national research around natural disasters.[341] UQ's Wind Research Laboratory also has capabilities in characterising and modelling the potential impacts and emergency response requirements of natural hazards, like wind storms and cyclones,[342] and has previously applied novel radar technologies in the detection and 'nowcasting' of hail storms.[343] In addition to Queensland's research expertise in natural hazards and disasters, the state also houses JCU's Cyclone Testing Station, which is used to test the robustness of homes and low-rise buildings to extreme weather events.[344] Queensland's deep knowledge of natural hazards offers fertile grounds for more advanced disaster resilience and response capabilities using cutting-edge modelling and technologies.

Queensland's strength in innovative robotics. Queensland is home to nation-leading robotics research, CSIRO Data61's Robotics and Autonomous Systems Group and QUT's Centre for Robotics, along with Queensland Robotics – Australia's first robotic cluster[345] – and the Australian Centre for Robotic Vision.[263] The ARM Hub is also based in Brisbane and works with industry and academia to design and manufacture robotic solutions.[234] Queensland has active robotic research programs in areas such as aerospace, defence, agriculture, logistics, infrastructure, marine and environmental monitoring and response, healthcare and mining. Given the significant burden of natural hazards, there could be opportunities to deploy robots as first responders, working alongside emergency response teams to provide situational awareness, locate people in danger, clear debris and gather information.[346] Examples of disaster-related robots developed in Queensland include the OzBot Titan firefighting robot developed by BIA5,[347] inspection and mapping robots such as Emesent's Hovermap (a spin-out of CSIRO's Data61),[348] and Sky Grow's Growbots, autonomous tree-planting fleets for reforestation.[349]

Disaster technologies attract investment. Like in Australia, global investment in disasters has traditionally focused on post-disaster emergency response and recovery rather than disaster risk reduction and resilience.[350,351] Following the Black Summer bushfires, however, the Australian Government has announced an $88.1 million investment in bushfires and natural hazards research.[352] This funding will transition the current Bushfire and Natural Hazards CRC into a new 10-year national research centre focused on world-leading research into natural hazard resilience and disaster risk reduction.[352] A further $100,000 has been announced by the Australian Government to help fund 'FireTech Connect' – a world-first commercialisation program based on the Sunshine Coast that is designed to support Australian start-ups in commercialising innovative technology solutions for predicting, preventing, fighting and managing bushfire emergencies.[353] Australian entrepreneurs and investors have also invested in growing climate-focused start-ups, providing $75,000 for successful start-ups through the Startmate start-up accelerator.[354]

Emerging cluster of fire-tech start-ups on the Sunshine Coast. The Sunshine Coast is home to a growing network of start-ups focused on commercialising technologies to address natural disasters.[355] Examples include Fireball. International, which uses satellites and sensor technologies to quickly and accurately detect fires close to the point of ignition.[356] Fireball.International evolved from research conducted by USQ and the company has previously been contracted by the State of California in a $14.4 million deal to use their satellite technologies, which was able to detect the ignition of the 2019 Kincade fire within 66 seconds.[355] Others include Noosaville-based Helitak, which develops and manufactures compact and efficient water pumps and tanks for firefighting helicopters.[357] The bushfire technology incubator, FireTech Connect, is also based on the Sunshine Coast and has brought together a diverse range of companies working in bushfire technologies across Australia, the United States, Canada and Asia.[358] The local Noosa Shire Council has a vision for the region to become a leader in bushfire preparedness,[358] and this could represent the beginning of a broader disaster resilience and response technologies industry for Queensland.

Challenges and future opportunities

Defining the blurry boundaries of the industry. Disaster resilience and response technologies cover a broad spectrum of potential solutions, from the testing and development of disaster-resilient buildings and the prediction of extreme weather events, through to the use of autonomous systems in responding to a natural hazard and post-event monitoring and assessment. Given the breadth of activities and the industry's level of maturity, its boundaries and identity are yet to crystallise. However, this nascent industry reflects an opportunity for Queensland as there is a clear, current and increased urgency for dealing with future natural disasters due to their associated costs. In growing this industry, there may be value in focusing on specific areas of specialisation to accelerate scaling. For example, a specialisation in cyclone response and preparedness technologies could take advantage of Queensland's existing expertise in cyclones. Alternatively, Queensland could leverage its diversity of natural hazard expertise and experience to develop general-purpose disaster preparedness, response and recovery technologies. Government, in collaboration with industry and academia, could play a role in shaping this strategic direction and vision for the industry.

Repurposing existing technologies for disaster purposes. Queensland has developed a diverse portfolio of robotic technologies that are designed to function in harsh environments, such as mining and construction sites. Rather than developing new robots for disaster purposes, a greater return on investment could be achieved by designing robots that are reconfigurable and capable of being deployed for other uses. As a potential starting point for further research and development into this industry, the government could conduct an audit of existing robotic and other technologies to explore if and how these could be applied for disaster preparedness, response or resilience purposes. For example, DroneDeploy has applied their mapping and monitoring technologies developed for agriculture, construction and mining to monitor the Great Barrier Reef and assist with disaster recovery efforts.[359] This approach could have transferrable benefits for other industries that would benefit from robotic applications too. The United Kingdom's roadmap for emergency response and disaster relief robots similarly outlines opportunities to leverage existing research into autonomous vehicles that could be deployed in an emergency or disaster scenario.[360]

Building robotic manufacturing capabilities to address supply chain gaps. The ARM Hub was set up to support researchers and businesses in co-designing and developing commercial robotic solutions,[234] however, experts believed that there are still significant gaps in the manufacturing supply chain for robotics in Queensland. This can deter companies from coming to Queensland, as they would need to import parts from overseas, which gives rise to several risks. These limitations extend beyond disaster resilience and response technologies and impact Queensland's ability to design, develop and scale most types of industrial robots. Queensland has a strong advanced manufacturing network, which has been recognised by the World Economic Forum as a global Advanced Manufacturing Hub, providing opportunities to connect the sector with a global network of advanced manufacturing companies.[117] As the coordinators of this network, the Queensland Government could explore opportunities to capitalise on these capabilities to support the scalability and translation of disaster resilience and response robots and other robotic technologies from prototype to practice.

Understanding the impact on and role of the insurance sector. The insurance sector plays a key role in post-disaster recovery, with natural disasters costing Australian insurers an average of $1.2 billion in insured losses each year (2010–12 average).[361] Rather than supporting disaster preparedness and resilience, insurance is used as a disaster response measure and low-income households who are underinsured or uninsured can be disproportionately disadvantaged in recovering from disasters.[362] A reduction in insured losses through improved disaster preparedness and mitigation could impact the affordability of insurance for households, potentially reducing risks and premiums.[362] These improvements, driven in part by improved data and digital technologies, could also drive innovation within the insurance sector to provide novel insurance options,[362] potentially as a compensation for reduced revenues. Suncorp and RACQ have already introduced premium discounts to incentivise households to improve the cyclone-resilience of their homes.[362,363] The number of insurance technology companies in Australia is also growing rapidly, up 53% from 2018–19, driving innovation in insurance products and developing new ways to personalise and deliver value to customers.[364]

Related industry opportunity areas

- **Green metal manufacturing:** potential overlap between these industries in terms of their workforce requirements and enabling technologies (e.g. robotics, autonomous systems)
- **Resource recovery technologies:** the e-waste generated by this sector could be repurposed through resource recovery processes
- **Construction technologies:** potential overlap between these industries in terms of their workforce requirements and enabling technologies (e.g. robotics, autonomous systems)
- **AI-enabled healthcare:** opportunities to use AI in health-related responses to natural disasters and in managing acute increases in demand for healthcare services
- **Insurance:** opportunities to support the insurance sector in managing risk and responding to disaster events, whilst also potentially driving change and innovation in this sector
- **Agriculture:** potential beneficiaries of growth in this sector through improved tools for building preparedness and resilience to natural disasters
- **Tourism:** potential beneficiaries of growth in this sector through improved tools for building preparedness and resilience to natural disasters
- **Public administration and safety:** potential beneficiaries of growth in this sector through improved tools for building preparedness and resilience to natural disasters
- **Advanced manufacturing:** drawing upon advanced manufacturing capabilities to develop the technologies needed to support this industry

9 Construction technologies

Construction is an area that is ripe for robotics and other digital technologies, with analysis of Queensland industries identifying construction as one with a high potential for automation.[365] Construction workers can be exposed to harsh work environments and potential safety risks (e.g. lifting heavy loads or completing work in precarious environments) – tasks that may be actionable by a robot instead, improving worker efficiency and safety. A recent analysis by Sydney-based AI scale-up, Faethm, and the Australian Computer Society revealed that fixed robotics (i.e. robots that can handle and manipulate objects in a pre-specified manner), navigation robots (i.e. robots that use reinforcement learning and sensors to autonomously move around an unstructured environment) and process automation (i.e. algorithms that can complete tasks that are fixed, logical and rule-based) are likely to be the top technologies that will impact the construction sector over the next 15 years.[366]

Similar to robotic mining applications, there are opportunities for robots to take on the dull, dangerous and dirty tasks within the construction sector. For example, autonomous systems could be used to inspect established buildings or those under construction, or lift, handle and place heavy loads. Other applications include the use of robots or autonomous systems to monitor construction sites for record-keeping purposes. Future construction technologies could also include the use of new materials, such as the replacement of steel and concrete with timber in built environments, which has the potential to significantly reduce construction-related emissions.[367] This industry development opportunity draws upon Queensland's strong construction sector, as well its strengths in enabling expertise and research capabilities in robotics and autonomous systems and built environments. Construction technologies also present new opportunities to manage the challenges facing the construction sector, including using automation technologies on-site and off-site to better manage the waste generated by the sector.

There were 245 construction technology businesses in Queensland as at 30 June 2019 and this is projected to increase to 444 by 2030 (see Figure 22). These reflect firms that directly form part of the construction technologies industry, acknowledging that there will be other firms that form part of this new industry value chain, which also create economic and employment opportunities. These businesses are estimated to have created 1,164 direct FTE jobs and 2,243 indirect FTE jobs for Queensland currently and this is estimated to increase to 2,109 direct and 4,064 indirect FTE jobs by 2030 (see Figure 22). These projections are based on the estimated adjusted average annual growth rate of 5% over the next 10 years.

	2019	2030
	245 businesses	**444** businesses
	1,164 direct FTE jobs	**2,109** direct FTE jobs
	2,243 indirect FTE jobs	**4,064** indirect FTE jobs

To illustrate the potential growth of this sector based on current global growth rates, the number of firms and jobs were forecast using insights derived from published global growth estimates from a comparable or related sector. The 'smart building' market, which uses sensor and automation technologies to automate building functions to improve efficiency, safety and sustainability, is expected to grow at an average annual rate of 23% between 2020 and 2025.[368] Smart infrastructure is also being incorporated into cities, with the Consumer Technology Associations predicting that spending on smart cities will grow at 8.7% per year between 2015 and 2025.[368] Other estimates from Allied Market Research expect that the global market for IoT in construction will grow by 14% annually between 2020 to 2027.[369] The average of these figures was used to inform the estimate of global growth rates.

Demand drivers

Desire for safer workplaces. The construction industry has the one of the highest rates of workplace fatalities and injuries, with an average of 8 fatalities and 8,465 general workplace injuries each year between 2009–14.[370] Safe Work Australia estimates the national impact of injuries and illness in the construction sector to be $5.8 billion (2012–13 figure).[371] While robotics could provide significant productivity gains for the construction sector, the potential safety benefits are the main driver of robotic applications.[346] Laing O'Rourke, a multinational construction and engineering company, has developed Toolbox Spotter, a workplace safety product that uses AI to detect people and objects and alert operators if they are in a blind spot.[372] The company estimates that 15.4% of its recorded incidents between 2008–18 could have been prevented using this technology.[346] To improve safety outcomes, there are likely to be opportunities for the construction sector to adopt technologies and solutions developed in other heavy industries, like mining, that have similar safety concerns and operate in harsh environments.

Figure 22. Historical and projected (based on historical Queensland growth rate and global growth rate) number of GST-registered firms and total full-time equivalent jobs (including direct and indirect jobs) in the construction technologies industry in Queensland

Note. Years denoted by an asterisk (*) reflect forecasted years.

Why Queensland?

QUEENSLAND'S POTENTIAL CONSTRUCTION TECHNOLOGIES INDUSTRY AT A GLANCE	
Demand drivers	• Reducing the safety risks for workers in the construction industry through assistive technologies • Improving productivity in the construction sector, which has been on the decline since the 2013–14 peak in the resources boom • Using automated technologies as a solution to potential future labour shortages brought about by a declining apprenticeship base and an ageing workforce • The imperative to address the sizeable waste problem for the construction sector and the opportunities to use robotics to improve resource recovery efforts • Alternative building materials, such as engineered wood products, would reduce the carbon footprint associated with building and construction
Supply drivers	• Research capabilities in digital and information technologies for built environments • Queensland's strengths in robotics and autonomous systems research • A network of regional advanced manufacturing hubs and good railway connectivity as the foundations to expand the state's prefabrication building activities
Challenges and future opportunities	• Identifying opportunities to develop or repurpose existing technologies for other construction applications to improve the return on investment for companies • Opportunities to use public procurement criteria to incentivise companies to adopt construction technologies and leverage productivity and safety gains

Potential for efficiency gains in the construction sector. The construction sector is a significant component of Queensland's economy, employing 221,802 people as of August 2020 (9.1% of the labour force).[36] The sector generated $26.6 billion in gross value-added production in 2018–19 (7.5% of GSP), making construction the third-largest contributor to the Queensland economy behind mining (12.2%) and healthcare (7.6%).[104] Productivity in the construction sector peaked in 2013–14 from the resources investment boom, but has since shown a downwards trajectory, with productivity levels in 2019 dropping to the levels previously seen in 2000.[373] Robotics and automation are expected to provide significant dividends for the Queensland economy, with research by Synergies Economic Consulting and QUT estimating these technologies will provide an additional $77.2 billion in GSP and 725,810 jobs over the next 10 years under the 'most likely' scenario.[365] While there is no estimate for the impact of robotics and automation on the construction sector, the sector's share of this additional GSP could be equivalent to $5.8 billion over the next decade, assuming these technologies will enable the sector to generate similar, if not better, economic contributions in the future.[104]

Potential future labour shortages. While the number of apprentices and trainees in-training in the construction sector is increasing, commencements and completions have plateaued or declined (see Figure 23). The construction labour force is also ageing, with the proportion of employed persons aged 55 years or over increasing from 10.6% in 2000 to 15.9% in 2020.[36] These trends pose a potential risk to the future talent pipeline for the construction sector.[36] An ageing workforce has been a strong driver of automation in the construction sector in Japan, which has experienced accelerated impacts of an ageing population.[374] Leading Japanese construction technology companies, such as Komatsu, Shimizu and Fujita, have developed a range of autonomous and software tools for the construction sector.[374] For example, Shimizu has used construction robots in high-rise building sites to assist with moving materials, welding and installing ceiling boards.[375] Robots could help fill labour shortages in Queensland's construction sector and provide solutions to countries facing similar challenges.[375]

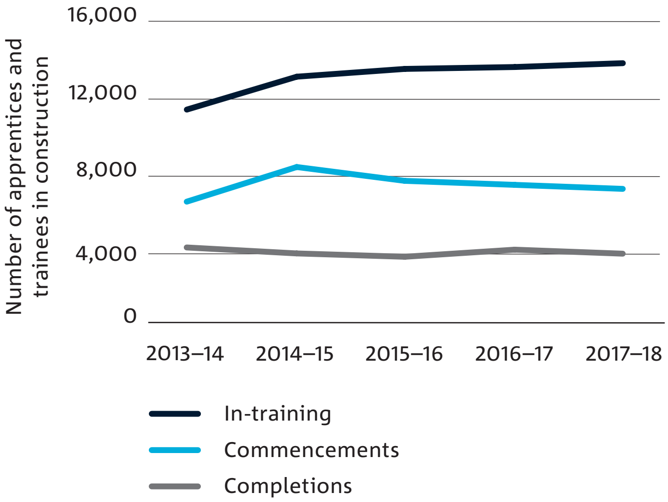


Figure 23. Number of commencements, completions and in-training for construction trade worker apprentices and trainees in Queensland

Data source: Queensland Government Department of Employment, Small Business and Training[376]

Improve resource recovery for the construction sector. Queensland generated around 5.2 million tonnes of construction and demolition waste in 2018–19, 42% of which ended up in landfill.[144] While resource recovery rates have been improving for construction and demolition waste, particularly for concrete, asphalt and ferrous metal,[144] this waste stream remains the largest contributor to landfill waste in Queensland (see Figure 24). Robots and other automation technologies could be used to improve resource recovery rates in the construction sector. Exemplar global leaders in automated recycling technologies include AMP Robotics – a Canadian firm that uses computer vision, machine learning and robotic automation to sort a range of waste streams[377] – and ZenRobotics – a Finnish AI-powered waste robotics company, which has recently partnered with a Finnish environmental management firm, Remeo, to develop a fully automated resource recovery facility for commercial waste streams, including construction and demolition waste.[378] Both companies have been successful in securing venture capital funding of approximately $23 million and $17 million, respectively.[377,379] The benefits provided by automating waste management processes in the construction sector are likely to have flow-on benefits for broader resource recovery efforts too.

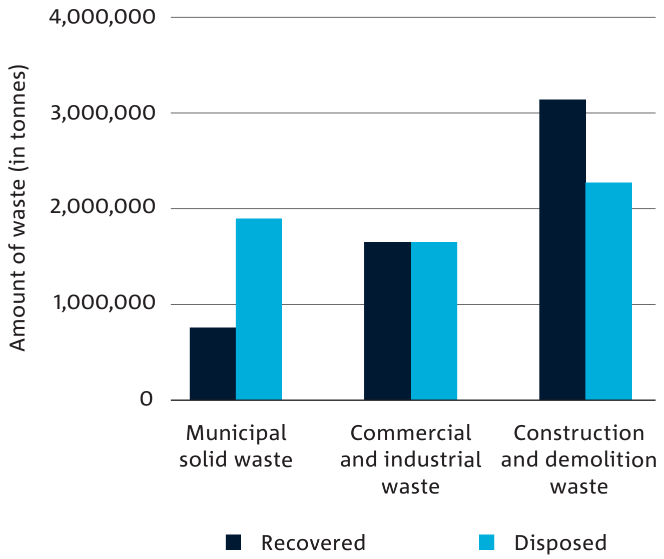


Figure 24. Amount of disposed and recovered waste generated in Queensland by waste stream

Source: Queensland Government[144]

Reduce emissions by switching to timber. The Queensland building sector accounts for 14% of the state's total carbon emissions.[380] A key driver of the embodied emissions associated with the building sector is the construction materials that are used, with concrete, cement, plasterboard, brick, iron and steel making up a large share of emissions.[381] Engineered wood products in the form of cross- or glue-laminated timber have been suggested as alternative building materials given timber is associated with fewer CO_2 emissions, is lighter weight, faster to install, aesthetically pleasing and adaptable for prefabricated modular design, whilst still maintaining comparable strength to conventional materials.[382] The engineered wood products market in Australia is nascent, generating approximately 50,000 m^3 of cross-laminated timber per year and valued at around $100 million in 2020.[382] There are signs of growth in engineered wood products in Queensland, with Hyne Timber recently opening a $23 million glue-laminated timber processing plant in Maryborough.[383] These industry developments have the potential to add greater value to Queensland's existing wood resources and generate novel regional job opportunities. Moreover, growth in building materials that are more suitable to prefabricated modular design might support greater uptake of both on-site and off-site automated construction technologies (see *Network of regional advanced manufacturing hubs* driver below).

Supply drivers

Queensland's expertise in applying technologies in built environments. QUT researches the use of information technologies in building and infrastructure projects, particularly building information modelling,[384] and are partners in the Building 4.0 CRC, focusing on the use of emerging technologies, data science and AI to develop new building processes.[385] Other relevant research groups include Bond University's Centre for Comparative Construction Research, which conducts research into the design and construction of built environments and uses virtual and augmented reality technologies to improve the safety and productivity of the sector,[172] and UQ's Centre for Future Timber Structures, which is developing innovative technologies for timber-based construction.[386] CSIRO Data61's Robotics and Autonomous Systems Group has also developed a range of autonomous and intelligent technologies that could be deployed in the construction sector.[387] These include Magnapods – legged robots that are highly flexible and can be used to inspect ferrous structures and confined environments – and Zebedee – a handheld laser scanner that quickly maps difficult 3D environments.[387] This expertise in built environments and enabling technologies could support Queensland's construction sector in becoming more digitally enabled.

Opportunities to draw upon strengths in computer vision and grasping robotics. The Australian Centre for Robotic Vision has world-leading capabilities in robotic vision, which can support the development of robots that are capable of understanding and navigating their environment.[263] The Centre's capabilities in robotic vision and grasping were demonstrated at the 2017 Amazon Robotics Challenge, where a team of researchers from the Centre won the challenge for a robot that was capable of picking up and stowing items in a warehouse – a difficult task for Amazon to automate in its warehouse.[388] These technologies were spun out through LYRO Robotics, which has recently secured seed funding from Toyo Kanetsu, a Japanese manufacturer, to commercialise their products.[389] These capabilities, combined with Queensland's broader AI and robotic capabilities, could be leveraged to support the development of construction technologies that can monitor progress on sites for quality and safety purposes; fetch tools and supplies; accurately scan and photograph sites; process scans against 3D building models; and complete routine tasks like bricklaying, painting and building timber or steel trusses.[346,365,366]

Network of regional advanced manufacturing hubs. Prefabrication (also referred to as offsite manufacturing) is not a novel concept, but has gained traction with developments in advanced manufacturing technologies.[390] It offers the potential for triple-bottom-line benefits for the construction sector, improving the quality and safety of construction, reducing construction time and decreasing waste.[390,391] Australia has been slow to adopt prefabricated housing and buildings compared with global leaders like Sweden.[392,393] An analysis of the construction sector in Western Australia identified manufacturing, transportation, logistics and site operations as key areas underpinning its success in building its prefabrication industry.[390] With a network of regional advanced manufacturing hubs,[394] and rail connectivity between major coastal regions, there is an opportunity for Queensland to grow its prefabrication building industry, potentially using robotic technologies to assist with onsite construction.[395] The technology in Queensland has the potential to be exported to countries that highly rely on prefabrication, such as Asia, Europe and North America.

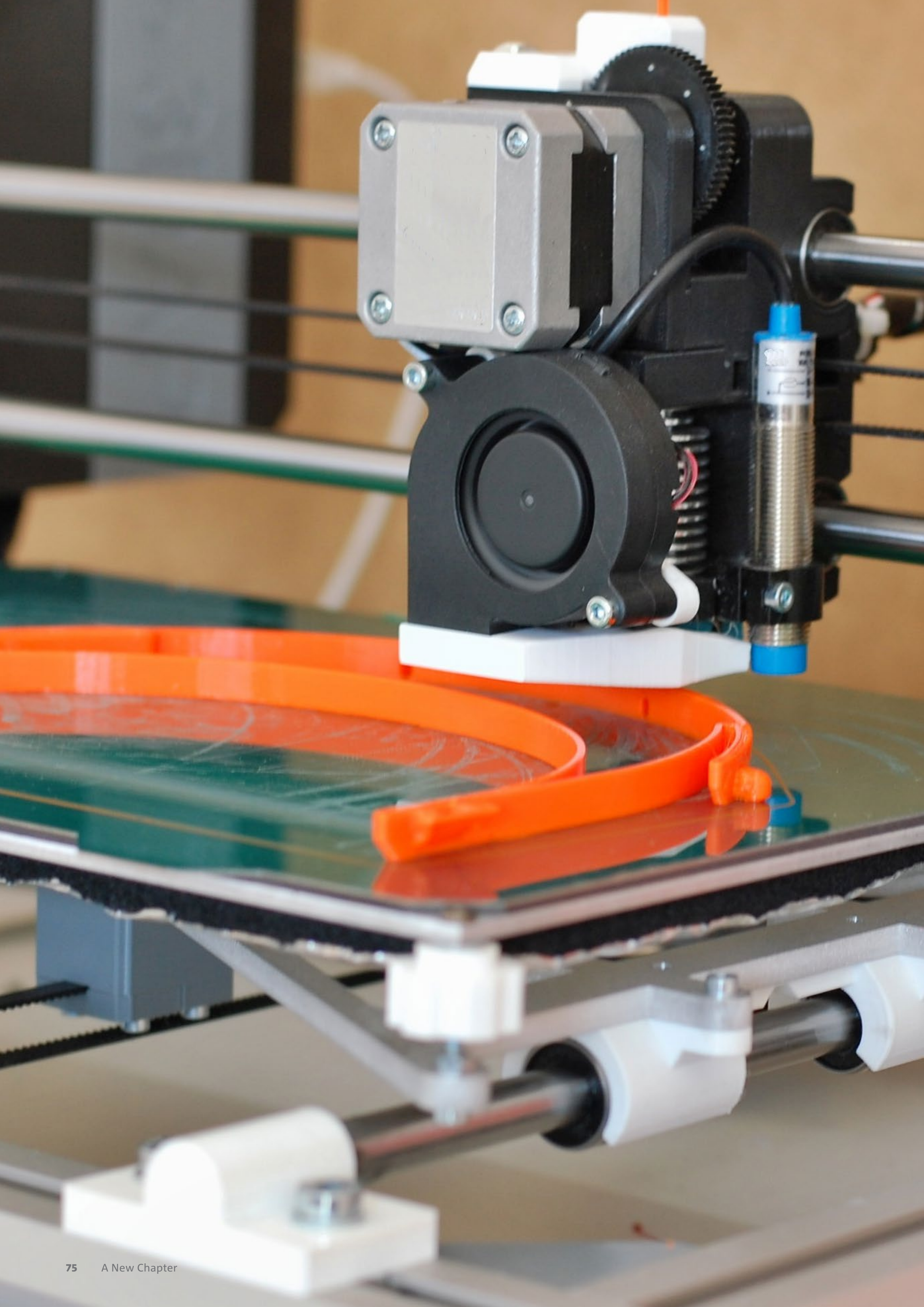
Challenges and future opportunities

Ensuring construction technologies are fit for purpose. Robots and autonomous systems traditionally perform well in routine, structured environments, but advances in robotic vision mean robots can now take on increasingly complex and unstructured tasks.[346] But experts noted that not all routine tasks will be automatable as the nature of the task depends on the context, which adds complexity. Consequently, it can be difficult for construction companies to justify the return on investment for a robotic system if it can only be used for a specific purpose or in a specific context.[396] Similar to the disaster resilience and response technologies industry, there may be value in identifying opportunities to repurpose existing robots for construction purposes or developing robots that have multiple functions to improve the return on investment. As robotic vision improves, however, construction technologies are likely to become more sophisticated and capable of completing or assisting in increasingly complex tasks. Moreover, adoption of construction technologies could also be enhanced by designing structures or construction activities for robotic construction, which could improve the safety and efficiency of assembly onsite.[397]

Using public procurement criteria to incentivise adoption of construction technologies. Robotic applications are currently costly for construction companies, which is one of the top factors that can act as a deterrent to adoption.[396] Even though these technologies could provide productivity, it is challenging for companies to fund the upfront investment required to test new technologies, particularly for small-to-medium-sized firms.[396] Infrastructure contracts can be highly competitive and construction companies will often have to reduce their costs to be competitive, meaning that there is limited incentive to invest in costly new technologies.[396] Having said that, as the construction workforce ages and retires over the next decade, and as the cost-competitiveness of technologies improves, experts felt the uptake of construction robotics and automation technologies may become more attractive for companies to fill this productivity void. One way that the government could accelerate the uptake of construction technologies and stimulate demand in this sector could be by adding criteria to tenders, such as technical and innovative merits, which encourage investment in innovation in the construction sector.[396]

Related industry opportunity areas

- **Green metal manufacturing:** potential overlap between these industries in terms of their workforce requirements and enabling technologies (e.g. robotics, autonomous systems)
- **Disaster resilience and response technologies:** potential overlap between these industries in terms of their workforce requirements and enabling technologies (e.g. robotics, autonomous systems)
- **Resource recovery technologies:** the e-waste generated by this sector could be repurposed through resource recovery processes
- **Construction:** construction technologies have the potential to improve the safety outcomes of the construction sector and protect against productivity challenges in the future
- **Advanced manufacturing:** drawing upon advanced manufacturing capabilities to develop the technologies needed to support this industry
- **Waste management, treatment and remediation:** using construction technologies to better manage the waste generated by the construction sector



Conclusions

This report presents a set of emerging seed industries that could support the next evolution of Queensland's knowledge economy, providing new sources of industry growth and attraction, job creation, regional development and export diversification. These nine candidate opportunity areas, while not exhaustive of all the potential opportunities available to Queensland, reflect the intersection of supply and demand drivers that point to emerging shifts in local, national and international markets and landscapes. Queensland's science and research sector sits at the core of each of these opportunities, providing the knowledge engine needed to drive innovations, discoveries and enabling technologies to give the state its competitive edge.

The potential size of each industry opportunity was quantified in terms of the number of firms and direct and indirect FTE jobs. Out of the nine seed industries identified in this report, green metal manufacturing has the potential to generate the largest number of firms and jobs for the state based on the current growth trajectory observed across Queensland firms. Other industries with sizeable job creation opportunities include AI-enabled healthcare and agricultural sensors and automation industries, which each have the potential to generate over 10,000 FTE jobs for Queensland. A significant share of these opportunities would likely be in the form of indirect FTE jobs arising from the flow-on impacts of these industry developments on other related industries.

Importantly, the seed industries presented in this report do not reflect an exhaustive list of areas where Queensland has a comparative advantage for new industry developments. Instead, it reflects a starting point for exploring new sources of diversification and growth for the state's economy. Other opportunity areas could include green cement and concrete, which, similar to metal manufacturing, are currently carbon-intensive. Current work at USQ is exploring opportunities for sustainable concrete using industrial waste.[398] Moreover, Queensland has leading capabilities in infectious disease research and vaccine development, which have been highlighted in the course of the COVID-19 vaccine development.[399] As such, vaccine development, therapeutics and immunotherapies could reflect another potential seed opportunity . Finally, protected cropping could provide new avenues for Queensland horticulture producers to mitigate the impacts of pests and climate variability. The Queensland Government is a partner in the CRC for Developing Northern Australia's protected cropping project, which is testing the technologies and agronomic practices that would support a scalable commercial cropping sector in tropical Australia.[400]

This report explored the current challenges that could limit the future growth and development of the knowledge-driven seed industries, highlighting a range of barriers and potential solutions in areas such as regulation, public policy, access to skilled workers and the capabilities and cost of enabling technologies, among others. While the challenges facing each opportunity will be unique, several common themes emerged across this cluster of potential seed opportunities. These areas of overlap include:

- The need to develop strong business ecosystems that consist of mature, established firms, innovative start-ups and cutting-edge researchers. While many of the industry opportunities discussed in this report have a small but growing cluster of firms, these firms are often small-to-medium-sized enterprises that may lack the capital needed to invest in scaling their innovations and technologies. By leveraging the supply drivers that position Queensland well to grow these seed industries, the state could focus its sights on attracting larger international firms to the state to drive momentum around a given industry.
- The transferability of skilled workers from other existing industries in Queensland, particularly those that may be at risk of future decline. Indeed, many of the knowledge-driven seed industries draw upon core capabilities found in industries such as manufacturing, professional, scientific, and technical services, agriculture, construction and engineering. With the right education, training and upskilling pathways, workers could find opportunities to transfer their capabilities into new industries. Moreover, these industries present new job creation opportunities for the next generation of graduates too, which will likely be in skilled, knowledge-driven domains. These new opportunities could assist traditional industries in attracting emerging talent and shifting out-dated negative perceptions around career pathways.
- The positioning of advanced manufacturing at the core of the majority of emerging knowledge-driven seed industries. While the Australian manufacturing sector operates on a smaller scale and complexity than other G20 countries, it has the necessary drivers (e.g. technology and innovation, human capital, institutional framework, etc.) needed to accelerate growth and leapfrog into a new paradigm.[401] The combination of Queensland's strengths in manufacturing and its other geographical, workforce and research and development strengths position the state in a strong position to gain a competitive edge, both domestically and globally. In the case of robotics manufacturing, this could involve expanding current advanced manufacturing capabilities into new domains, such as high-value robotic manufacturing.

- The role for government in supporting and incentivising the growth of new markets. Given the emerging nature of the seed industries presented in this report, the domestic markets for some of these sectors are small, but with potential export opportunities. There could be a role for government in seeding initial domestic demand for these industries; for example, by procuring products made using recycled content, or incentivising uptake of clean energy sources in green metal manufacturing. Alternatively, government, in collaboration with industry, could support firms within these seed industries in developing strategies that are specifically focused on the emerging export opportunities associated with these sectors.
- The need for contemporary and adaptive regulatory systems that encourage growth and innovation. Each of the knowledge-driven seed sectors are underpinned by technologies that are constantly evolving, which presents a challenge for the government to ensure the regulatory environment keeps pace. By working with industry and academia to explore the potential future risks and opportunities presented by these emerging technologies, government can proactively ensure it strikes the right balance between protecting economic, social and environmental interests whilst still encouraging the future growth and development of these seed sectors.
- The transferability between the knowledge-driven seed industries and existing industries. None of the seed industries explored in this report operate in isolation. Rather, the growth of any one of these seed industries will likely have flow-on benefits for other emerging and established sectors through the increased demand for firms that form part of the industry's value chain or the stimulation of research and development activities that can be applied in other industrial applications. For example, growing Queensland's robotic manufacturing capabilities will not only benefit applications in disaster resilience and response, but will also prove useful in applying robotic technologies in other sectors (e.g. construction, agriculture, healthcare, mining, advanced manufacturing, etc.).

For any of the nine knowledge-driven seed industries presented in this report, strong leadership, strategic direction and collaboration across government, industry and academia will be needed to drive the opportunities forward. Instead of relying on incremental changes, these industries present opportunities to seed new sources of economic growth and job creation for Queensland, driven by cutting-edge science, technology and innovation. The COVID-19 pandemic has caused significant disruption to the Queensland economy and abroad, but with this disruption comes an opportunity to set a new strategic direction for the state towards a 'new normal' for economic development that has knowledge at its core.

Appendix: Project methodology

Defining knowledge-driven seed industries

In 2019, CSIRO's Data61 released the *New Smarts* report, which outlined a set of knowledge-intensive industry clusters that are likely to emerge in Queensland over the coming decade. Building on this previous work, this project commenced by reviewing the meta-themes within the *New Smarts* report to define the scope of the present study, understand the current state of Queensland landscape and identify any changes that have emerged since the release of the report in 2019, particularly in the event of recent disruptions (e.g. the 2019–20 Black Summer bushfires, the global COVID-19 pandemic, geopolitical shifts).

The scoping review was followed by a detailed horizon scan, where the project team conducted a series of scoping interviews with key domain-general experts to identify broad opportunity areas, which were interrogated further with desktop research. This stage identified potential candidate knowledge-driven seed industry opportunities and explored the trends, drivers and areas of comparative advantage supporting the future growth of these opportunity areas for Queensland. These candidate seed industries were then screened, refined and prioritised according to their feasibility (e.g. existing business ecosystem, research and development capabilities, workforce availability, etc.), scalability (e.g. size of local and global markets, use of existing Queensland supply chains, transferability of opportunity to other contexts) and novelty (e.g. absence of existing industry development initiatives). This resulted in the identification of nine knowledge-driven seed industries.

To validate and gain more detailed insights into these selected industry opportunities, the project team conducted a series of investigative interviews with domain-specific experts who were actively working in the nine selected seed industries. These consultations served to identify additional trends, drivers and areas of comparative advantage. The experts also provided comments on the current barriers limiting future growth and industry attraction, and potential solutions for addressing these challenges in the future. These insights were complemented with further intensive desktop research to characterise and define each of the knowledge-driven seed industries and estimate the potential size of each sector in 2019 and projected out to 2030 (see *Estimating the size of seed industries* section).

Estimating the size of seed industries

Accurately understanding the number of firms operating directly within emerging seed industries and estimating their potential impact on the economy is critical for advocacy for the industry and monitoring progress of initiatives. Using standard traditional top-down satellite accounting approaches to define industry categories using the Australian and New Zealand Standard Industrial Classification (ANZSIC) scheme, however, can result in gross overestimation of the size of these seed industries. Conversely, developing lists of known companies, without an underpinning population framework, such as the Australian Business Registrar (ABR), can result in a significant underestimation.

To determine the size of each knowledge-driven seed industry in this report, we adopted 'data-driven satellite proxy' analysis, which implements text mining and bibliometrics[402] to identify and flag businesses with characteristics of the seed industry. Keywords that describe the industry, as well as exemplar firms that operate within the industry currently, were identified through extensive desktop audits and consultation with key experts in each seed industry (see Table 2 for list of keywords). The approach identifies seed industry 'characteristic firms'. Characteristic firms are firms with an Australian Business Number (ABN) that would cease to exist in their present form, or would be significantly affected, if the seed industry did not exist (e.g. due to no demand or market intervention). This definition is similar to the characteristic firms identified by satellite accounting frameworks, which apply a general approach to determine the contribution of non-standard industries to an economy, generally through a top-down data allocation approach (see, for example, the tourism satellite account[403]). Unlike traditional top-down satellite accounting approaches, however, the proxy technique provides greater granularity in identifying and estimating the number of firms that precisely form part of an emerging industry. It also provides opportunities to assess the impact of policy, programs and initiatives specifically on the industry.

To count the number of ABN firms, a 'data-driven satellite proxy' flag was constructed for each new seed industry by applying the keywords to various text variables in the Longitudinal Australian Business Integrated Intelligence (LABii) datavault (e.g. name of firm, procurement description, patent, trademark, plant breeder or design description, etc.) to flag the firms and derive a count of the number of Australian Business Number (ABN) unique firms. LABii is a micro-datavault developed by Moyle, Pandey and Stern in QUT's Australian Centre for Entrepreneurship Research and Centre for Data Science.[404] LABii is comprised of separate public and non-public datasets like ABR, Intellectual Properties Australia (i.e. a register on patents, trademarks, design and plant breeder's rights), listings of the Australian Stock Exchange, the Register of Australian Mining exports and data on exports, mergers and acquisitions. LABii is longitudinal, including business entries since June 1999, and all data used in this analysis are current to the year ending June 2019.

Once the number of firms in each seed industry were identified, the list was verified by two researchers. For this analysis, we excluded non-GST-registered ABN firms, included only those firms that are ABN active at 30 June in a given year and count an ABN once for Queensland, even if they may have multiple trading locations in the state. Table 1 details the methodology for calculating the standard full-time equivalent (FTE) jobs associated with the seed industry firms.

As with all research, there are limitations with the methodology implemented in this report. The estimation of the seed industry may not have captured all ABN firms in the seed industries or may have erroneously captured others. Given the emerging nature of these seed industries and the limited amount of information on them, combined with the gross overestimation of the top-down approach to identify these sectors, the approach we have adopted is considered to be leading edge.

In addition, accurate projection of the growth path of fast-emerging, transformative seed industries is difficult as it is influenced by many factors and nuances of the diffusion of the new sector within the context of the external environment. While prior studies in evolutionary economics suggest that the diffusion of new sectors commonly starts slow, speeds up, then finally converges, this trajectory is not always consistent.[407] Indeed, riskier and more novel technologies tend to have a longer initial kick-off time, sometimes as long as 20 years before a convergence commences.[408] Consequently, taking into account both historical growth rates and global trends is considered to be the most appropriate predictor of sectoral growth.

Table 1. Standard full-time equivalent (FTE) jobs methodology

JOB TYPE	PROCEDURE
Direct FTE jobs	To calculate direct FTE jobs, the following procedure was used: • Divide the number of employed people in Queensland by the number of businesses in June 2019 to derive average employees per firm.[405,406] • Separate this average number of employees into full-time and part-time employment based on 69% full-time and 31% part-time as per the original series in the labour force statistics for Queensland.[405] • Multiply the average number of full-time and part-time jobs by the number of seed industry businesses. • Calculate FTE jobs: *Full-time jobs* + (*Part-time jobs* / 2)
Indirect FTE jobs	To calculate indirect FTE jobs, the value-added indirect benefits were divided by the value-added required to create an FTE job either at the Queensland level for broad economic, social and environmental benefits, or the industry sub-division level for the value chain indirect benefits.

Table 2. Keywords and connected Australian and New Zealand Standard Industrial Classification (ANZSIC) sub-division codes used to define firms in the nine knowledge-driven seed industries and their value chain

SEED INDUSTRY	KEYWORDS	CONNECTED ANZSIC SUB-DIVISIONS
Additive biomanufacturing	3D digital scan*; 3D model; 3D implant; 3D organ; 3D print*; 3D system; additive biomanufact*; binder jet*; biofab*; bioink; biomanufact*; bio-manufact*; biomechanic; biomed*; biomimetic; bionic; biopolymer; bioprint*; bioscan*; custom implant; custom surgical; electron melting; energy simulation; fused deposition model*; implant; material extrusion; material jetting; medical tech*; medtech; metal laser sintering; multi jet fusion; personalised device; personalised health; precision health; regenerat* medic*; reinforcing natural fibre; selective laser melting; selective laser sintering; tissue morph*	**18** Basic Chemical & Chemical Product Manufacturing; **19** Polymer Product & Rubber Product Manufacturing; **20** Non-Metallic Mineral Product Manufacturing; **21** Primary Metal & Metal Product Manufacturing; **22** Fabricated Metal Product Manufacturing; **24** Machinery & Equipment Manufacturing; **34** Machinery & Equipment Wholesaling; **42** Other Store-Based Retailing; **59** Internet Service Providers, Web Search Portals & Data Processing Services; **66** Rental & Hiring Services (ex. Real Estate); **69** Professional, Scientific & Technical Services (ex. Computer System Design & Related Services); **70** Computer System Design & Related Services; **81** Tertiary Education; **84** Hospitals; **85** Medical & Other Health Care Services
AI-enabled healthcare	agile health; artificial intelligence; automated health; clinical data; digital health; elder* monitor*; electronic health record; medical records; health computer vision; deep learning; health device; health genomics; health imaging; health imagery; health surveillance; health interoperability; machine learning; health monitoring; natural language; pattern recognition; health robotics; health equipment; intelligen* health; medical record automation; precision medicine; telehealth; wearable health; electronic health record; wearable; medical device; medical equipment; medical laboratory; health data; health analytics; health digitisation; health innovation; health 4.0; health 5.0;	**24** Machinery & Equipment Manufacturing; **34** Machinery & Equipment Wholesaling; **58** Telecommunications Services; **59** Internet Service Providers, Web Search Portals & Data Processing Services; **63** Insurance & Superannuation Funds; **66** Rental & Hiring Services (ex. Real Estate); **69** Professional, Scientific & Technical Services (ex. Computer System Design & Related Services); **70** Computer System Design & Related Services; **75** Public Administration; **81** Tertiary Education; **84** Hospitals; **85** Medical & Other Health Care Services; **86** Residential Care Services; **87** Social Assistance Services
Green metal manufacturing	carbon free aluminium; carbon free energy; carbon free iron; carbon free manufact*; carbon free metal; carbon free steel; carbon free zinc; carbon free; carbon low aluminium; carbon low energy; carbon low iron; carbon low manufact*; carbon low metal; carbon low steel; carbon low zinc; carbon neutral; clean aluminium; clean energy; clean energy; clean iron; clean manufact*; clean metal; clean steel; clean zinc; emission aluminium; emission energy; emission iron; emission manufact*; emission metal; emission steel; emission zinc; fossil free aluminium; fossil free energy; fossil free iron; fossil free manufact*; fossil free metal; fossil free steel; fossil free zinc; green aluminium; green energy; green iron; green manufact*; green metal; green steel; green zinc; hydrogen; hydropower; low carbon; low emissions solar; sustainable aluminium; sustainable energy; sustainable iron; sustainable manufact*; sustainable metal; sustainable steel; sustainable zinc; wind power; zero emissions;	**06** Coal Mining; **07** Oil & Gas Extraction; **08** Metal Ore Mining; **09** Non-Metallic Mineral Mining & Quarrying; **10** Exploration & Other Mining Support Services; **18** Basic Chemical & Chemical Product Manufacturing; **19** Polymer Product & Rubber Product Manufacturing; **21** Primary Metal & Metal Product Manufacturing; **22** Fabricated Metal Product Manufacturing; **23** Transport Equipment Manufacturing; **24** Machinery & Equipment Manufacturing; **26** Electricity Supply; **27** Gas Supply; **30** Building Construction; **31** Heavy & Civil Engineering Construction; **32** Construction Services; **59** Internet Service Providers, Web Search Portals & Data Processing Services; **66** Rental & Hiring Services (ex. Real Estate); **69** Professional, Scientific & Technical Services (ex. Computer System Design & Related Services); **81** Tertiary Education

SEED INDUSTRY	KEYWORDS	CONNECTED ANZSIC SUB-DIVISIONS
Resource recovery technologies	agricultural waste; agrochemical; anaerobic digestion; battery waste; bioeconomy; bioenergy; biofertiliser; biofuture; biomanufacturing; biomass; bioprocessing; bioproducts; biowaste; by-product; circular economy; circular practice; compost; construction waste; containers for change; demolition waste; digestate; electr waste; emission; e-waste; food organic; food security; food waste; garden organic; gasification; greenhouse gas; green waste; high value product; life cycle assessment; methane; municipal solid waste; nitrous oxide; nutrient security; organic recycling; organic waste; plastic waste; pyrolysis; recycled material; recycled plastic; recycled textile; recycling; resource recovery; supply chain; techno-econom*; waste buil*; waste conversion; waste energy; waste glass; waste manag*; waste recovery; waste stream; waste water;	**01** Agriculture; **05** Agriculture, Forestry & Fishing Support Services; **11** Food Product Manufacturing; **12** Beverage & Tobacco Product Manufacturing; **13** Textile, Leather, Clothing & Footwear Manufacturing; **15** Pulp, Paper & Converted Paper Product Manufacturing; **16** Printing (include. Reproduction of Recorded Media); **17** Petroleum & Coal Product Manufacturing; **18** Basic Chemical & Chemical Product Manufacturing; **19** Polymer Product & Rubber Product Manufacturing; **20** Non-Metallic Mineral Product Manufacturing; **21** Primary Metal & Metal Product Manufacturing; **22** Fabricated Metal Product Manufacturing; **24** Machinery & Equipment Manufacturing; **26** Electricity Supply; **27** Gas Supply; **28** Water Supply, Sewerage & Drainage Services; **29** Waste Collection, Treatment & Disposal Services; **44** Accommodation; **45** Food & Beverage Services; **46** Road Transport; **59** Internet Service Providers, Web Search Portals & Data Processing Services; **66** Rental & Hiring Services (ex. Real Estate); **69** Professional, Scientific & Technical Services (ex. Computer System Design & Related Services); **75** Public Administration; **81** Tertiary Education
Microalgal and macroalgal	algae; algal; aquaculture; asparagopsis; biofertliser; bioflora; biofuel; bioremediation; bioresearch; bioscience; biosynthetic; biotechnology; food supplements; functional food; high-value food; livestock feed; nutraceuticals; seaweed; therapeutic; value-added product; wastewater bioremedi*; wastewater remedi*; wastewater treat;	**01** Agriculture; **02** Aquaculture; **04** Fishing, Hunting & Trapping; **05** Agriculture, Forestry & Fishing Support Services; **11** Food Product Manufacturing; **17** Petroleum & Coal Product Manufacturing; **18** Basic Chemical & Chemical Product Manufacturing; **26** Electricity Supply; **27** Gas Supply; **28** Water Supply, Sewerage & Drainage Services; **29** Waste Collection, Treatment & Disposal Services; **69** Professional, Scientific & Technical Services (ex. Computer System Design & Related Services); **81** Tertiary Education
Agricultural sensors and automation	agricultur* sensor; agricultur* 4.0; agricultur* 5.0; agricultur artificial intelligence; agricultur* fintech; agricultur* digital; agricultur* cloud; artificial intelligence; agritech; agridigital; agtech; auto steer; automat farm; vertical farm; automat crop; automat drone; automat tractor; automat vehicle; automat weed; bioeconomy; biosecurity; blockchain prevenance; cloud computing; crop model; crop reflectance; agricultur* data; agricultur* analytics; agricultur* decision; agricultur* intelligen; agricultur* precision; decision support; deep learning; digital connectivity; digital farm; digital marketplace; driverless tractor; drone; edge computing; farm management; farm software; farm optimisation; farm robot; farm sensor; farm data; farm analytics; high-tech food; high-tech farm; high-tech agricultur*; indoor farm; precision irrigation; precision planting; precision spray; agricultur* mapping; farm mapping; protected farm; proximal sensing; remote cropping; remote sensing; sense and spray; sensor sprayer; smart contract; smart farm; smart pesticide; smart spray; smart tractor; soil sensor; survey drone; targeted pesticide; thermal image; unmanned aerial; variable rate technolog*; yield mapping	**01** Agriculture; **02** Aquaculture; Forestry & Logging; **04** Fishing, Hunting & Trapping; **05** Agriculture, Forestry & Fishing Support Services; **09** Non-Metallic Mineral Mining & Quarrying; **20** Non-Metallic Mineral Product Manufacturing; **23** Transport Equipment Manufacturing; **24** Machinery & Equipment Manufacturing; **34** Machinery & Equipment Wholesaling; **42** Other Store-Based Retailing; **58** Telecommunications Services; **59** Internet Service Providers, Web Search Portals & Data Processing Services; **66** Rental & Hiring Services (ex. Real Estate); **69** Professional, Scientific & Technical Services (ex. Computer System Design & Related Services); **70** Computer System Design & Related Services; **81** Tertiary Education

SEED INDUSTRY	KEYWORDS	CONNECTED ANZSIC SUB-DIVISIONS
Supply chain provenance technologies	authenticity; automat* agricultur*; biosecurity; blockchain; consumer intermedia*; crypto; counterfeit good; cross-border trade; digital storytelling; distributed ledger; farm authenticity; farm to fork; food fraud; food safety; food credentialing; food tracking; genetic testing; image recognition; international trade; internet of things; paddock to plate; produce fraud; produce safety; produce credentialing; produce tracking; producer intermedia*; prosumerisation; provenance; remote surveillance; sensors; smart contract; supply chain; traceability; traceable markers; trust	**01** Agriculture; **02** Aquaculture; Forestry & Logging; **04** Fishing, Hunting & Trapping; **05** Agriculture, Forestry & Fishing Support Services; **06** Coal Mining; **07** Oil & Gas Extraction; **08** Metal Ore Mining; **09** Non-Metallic Mineral Mining & Quarrying; **10** Exploration & Other Mining Support Services; **20** Non-Metallic Mineral Product Manufacturing; **24** Machinery & Equipment Manufacturing; **25** Furniture & Other Manufacturing; **28** Water Supply, Sewerage & Drainage Services; **29** Waste Collection, Treatment & Disposal Services; **34** Machinery & Equipment Wholesaling; **36** Grocery, Liquor & Tobacco Product Wholesaling; **42** Other Store-Based Retailing; **58** Telecommunications Services; **59** Internet Service Providers, Web Search Portals & Data Processing Services; **66** Rental & Hiring Services (ex. Real Estate); **69** Professional, Scientific & Technical Services (ex. Computer System Design & Related Services); **70** Computer System Design & Related Services; **81** Tertiary Education
Disaster resilience and response technologies	adaptation; bushfire; climate; disaster resilience; drought; emergency resilience; environmental modelling; extreme heat; extreme weather; firetech; fire tech; flood (& != light); hail; hazard; heatwave; natural disaster; natural hazard; pandemic; recover; response; safety risks; storm tide; tropical cyclone; wildfire	**09** Non-Metallic Mineral Mining & Quarrying; **21** Primary Metal & Metal Product Manufacturing; **22** Fabricated Metal Product Manufacturing; **23** Transport Equipment Manufacturing; **26** Electricity Supply; **28** Water Supply, Sewerage & Drainage Services; **29** Waste Collection, Treatment & Disposal Services; **30** Building Construction; **31** Heavy & Civil Engineering Construction; **32** Construction Services; **34** Machinery & Equipment Wholesaling; **35** Motor Vehicle & Motor Vehicle Parts Wholesaling; **42** Other Store-Based Retailing; **47** Rail Transport; 58 Telecommunications Services; **59** Internet Service Providers, Web Search Portals & Data Processing Services; **66** Rental & Hiring Services (ex. Real Estate); **70** Computer System Design & Related Services; **75** Public Administration; **76** Defence; **77** Public Order, Safety & Regulatory Services; **81** Tertiary Education; **85** Medical & Other Health Care Services; **87** Social Assistance Services
Construction technologies	3D mapping; building 4.0; built environment; commercial build*; construct* 4.0; construct* automat*; construct* robot; construct* technolog*; construct* waste; demolition waste; fixed robot; harsh environment; heavy industr*; laser scan*; magnapod; nail detection; navigat* robot; prefabricat*; process automat*; residential building; robotic grasping; robotic vision; screw detection; site monitor; unstructured environment; welding robots; workplace safety; zebedee	**09** Non-Metallic Mineral Mining & Quarrying; **20** Non-Metallic Mineral Product Manufacturing; **21** Primary Metal & Metal Product Manufacturing; **22** Fabricated Metal Product Manufacturing; **24** Machinery & Equipment Manufacturing; **29 30** Building Construction; **31** Heavy & Civil Engineering Construction; **32** Construction Services; **34** Machinery & Equipment Wholesaling; **42** Other Store-Based Retailing; **58** Telecommunications Services; **59** Internet Service Providers, Web Search Portals & Data Processing Services; **66** Rental & Hiring Services (ex. Real Estate); **67** Property Operators & Real Estate Services; **69** Professional, Scientific & Technical Services (ex. Computer System Design & Related Services); **70** Computer System Design & Related Services; **73** Building Cleaning, Pest Control & Other Support Services; **81** Tertiary Education

*All variations of the ending of the word were incorporated in the text mining and bibliometrics.

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