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Australia's National Science Agency

Critical Energy Minerals Roadmap

The global energy transition: Opportunities for Australia's mining and manufacturing sectors

Australian Government

Citation

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Acknowledgments

CSIRO acknowledges the Traditional Owners of the lands that we live and work on across Australia and pays its respect to Elders past and present. CSIRO recognises that Aboriginal and Torres Strait Islander peoples have made and will continue to make extraordinary contributions to all aspects of Australian life including culture, economy and science.

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We are grateful for the time and input of the stakeholders from industry, government, academia who were consulted throughout this project. A full list of stakeholders consulted may be found in Appendix C.

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Foreword

Australia's future economic prosperity will depend on how well we can use our vast energy and mineral resources to play to our strengths, and how well we can adapt to follow the global market shift towards zero emissions.

As we look to how we emerge from recession and rebuild our economy, critical energy metals present a tremendous opportunity for us to offer unique, high value products to the rest of the world.

The future global economy will be underpinned by technologies that depend on minerals such as such as lithium, graphite, cobalt, titanium and rare earth elements. These are essential to the advancement of many sectors, including high-tech electronics, telecommunications, transport and defence.

They are also vital to power the global transition to a low emissions economy, and the renewable energy technologies that will be required to meet the 'Net Zero' targets of an increasing number of countries around the world. Progress towards these targets will require trillions of dollars of investment in renewable electricity generating capacity, transmission, and storage technology.

But while the need for these minerals is great, the supply is not guaranteed. Many of these critical minerals are only available in a few locations around the world, and with the uptake of electric vehicles, battery, solar and wind technologies expected to soar over the next decade, countries are scrambling to secure a steady supply.

With our mineral wealth, Australia has the potential to become a critical energy minerals powerhouse.

Not by simply exporting raw minerals, but by upgrading our ores to metals, chemicals and alloys – and in some cases finished products for niche markets. Without this, we will only capture a fraction of these trillion-dollar markets.

It seems impossible when the rest of the world is so far ahead of us in adding value, but this is what science is for – delivering solutions to seemingly impossible challenges. As CSIRO, this is our Mission.

To capture this opportunity for Australia, we need to move up the value chain from exploration and extraction to processing, separation, refining and the manufacture of higher value products. By connecting our mining and manufacturing sectors in this way, we will also drive the growth of advanced manufacturing capabilities in Australia. Predicting the right market shifts, and picking the right products is wickedly difficult, but here again, science can lend a powerful hand.

There is a wealth of opportunity in front of us, but success will require a coordinated whole-of-sector effort. This Roadmap aims to chart a way forward by connecting Australia's mining and manufacturing industries to form a new, high value industry that can be a unique Australian success story.

We will only achieve this as Team Australia, and as Australia's national science agency, CSIRO is partnering widely across research, industry, and government to frame this dialogue and develop an innovation ecosystem to propel us forward.

This Roadmap is the product of numerous interviews with industry experts, government and scientists, and we are simultaneously forming a collaborative network around our **Critical Energy Metals Mission** in development to accelerate our progress. I say "our" mission because Missions like this are critical to our collective future, so they are everyone's mission.

We believe high value exports from critical energy metals can provide an important source of economic growth for Australia and help to power a global transition towards zero emissions.

Together, we can extract new value from our mining and manufacturing sectors, and give Australia a competitive advantage in a world undergoing massive change.

Dr Larry Marshall
Chief Executive
CSIRO

Glossary

APC	Advanced Propulsion Centre
ARENA	Australian Renewable Energy Agency
BEV	Battery electric vehicle
BMS	Battery management systems
BoP	Balance of plant
BSC	Battery Stewardship Council
CAM	Cathode active material
CdTe	Cadmium telluride
CEFC	Clean Energy Finance Corporation
CIGS	Copper-indium-gallium-selenide
C-Si	Crystalline silicon solar panels
CSP	Concentrated solar power
CT	Central tower
DRC	Democratic Republic of Congo
EDR	Economically demonstrated resources
EMM	Electrolytic manganese metal
EVs	Electric vehicles
FBICRC	Future Battery Industries Cooperative Research Centre
FBR	Fluidised bed reactor
FCEVs	Fuel cell electric vehicle
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
HPQ	High purity quartz or high purity silica
ICEs	Internal combustion engines
IP	Intellectual property
ISR	In-situ recovery
LCO	Lithium cobalt oxide batteries
LCOE	Levelised cost of energy
LFP	Lithium iron phosphate batteries
LiB	Lithium-ion batteries
Li-Metal	Lithium metal batteries
LiNMC	Lithium nickel manganese cobalt batteries (e.g. 111, 622 or 811)
LME	London Metal Exchange
LNG	Liquefied natural gas
Long-term	2040–2050
MEA	Membrane electrode assembly
Medium-term	2030–2050
MRIWA	Minerals Research Institute of WA
N	A scale of purity of materials based on the number of nines in the percentage purity
NAIF	Northern Australia Infrastructure Facility
LiNCA	Lithium nickel cobalt aluminium batteries
NdFeB	Neodymium iron boron
NdPr	Neodymium praseodymium
OEM	Original equipment manufacturer
P-CAM	Mixed metal hydroxide precursor
PEM	Proton exchange membrane
PERC	Passive Emitter and Rear Cells
PGE	Platinum Group Elements
P_2O_5	Phosphorous pentoxide
RD&D	Research development and demonstration
REE	Rare earth elements
REO	Rare earth oxide
Short-term	2020–2030
SOE	Solid oxide electrolysis
Solar PV	Solar photovoltaic
T&D	Transmission and distribution
V_2O_5	Vanadium pentoxide
VRE	Variable renewable energy
VRET	Victorian Renewable Energy Targets
VRFB	Vanadium redox flow batteries

Energy

GJ	Gigajoule (1,000,000,000 joules)
kW	Kilowatt (1000 watts of electrical power)
MW	Megawatt (1,000,000 watts of electrical power)
MWh	Megawatt hour, a megawatt of power used in an hour
GW	Gigawatt (1,000 megawatts of electrical power)
GWh	Gigawatt hour, a gigawatt of power used in an hour

Mass

t	Tonne (1,000 kilograms)
kt	Kilotonne (1,000 tonnes)
Mt	Megatonne (1,000,000 tonnes)

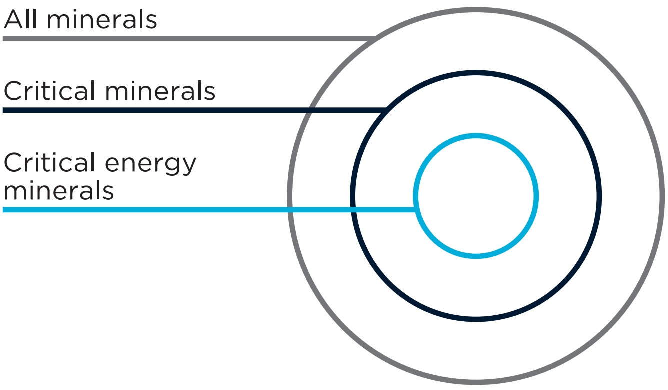
Executive summary

Report rationale

Why 'critical energy minerals'?

The global transition to renewable energy will be underpinned by technologies that require a broad range of critical minerals.

'Critical energy minerals' is an emerging theme that is explained by the convergence of two primary mining and energy sector trends. The first, 'critical minerals', represents a subset of minerals that are of growing concern due to potential supply risks and projected demand increases across a wide range of applications. Separately, the transition to renewable energy is underpinned by technologies that are more critical mineral intensive than fossil fuel incumbents and are expected to undergo accelerated growth over the coming decades.



Why Australia?

Australia's resource endowment and potential to play a major role in the global energy transition means that it is uniquely placed to capitalise on the emergence of critical energy minerals.

There are two primary factors unique to Australia that are driving further consideration of the nation's potential to derive value from critical energy minerals. Firstly, in contrast to key trading partners across Asia and Europe, Australia's economy is comprised of a large mining and comparatively small manufacturing sector. The emergence of critical energy minerals should therefore be recognised as an opportunity to capitalise on the nation's resource endowment by diversifying its export base and by adding value through the manufacture of more complex products.

Secondly, Australia's access to renewable energy resources such as solar and wind, combined with land availability and a skilled workforce means that it has the potential to become a renewable energy 'superpower'.[1] When considered in conjunction with the rich endowment of relevant minerals and broad R&D capabilities, Australia should also be developing domestic manufacturing supply chains to support the global deployment of these technologies. This will translate into higher productivity and an increase in both direct as well as indirect employment via the emergence of ancillary supporting services.[2]

Why now?

As global markets respond to the emergence of critical energy minerals, Australia now faces a strategic imperative to invest in relevant mining operations and associated technology value chains.

While a number of key renewable energy technologies have mature value chains, many are yet to hit a 'tipping point' which creates considerable scope for investment in new regions. Similar opportunities exist for less mature energy technologies with comparatively undeveloped supply chains.

Further, the market shifts occurring as a consequence of critical energy minerals are accelerating as countries and corporations continue to set net zero 2050 emissions goals and look to establish supply chain sovereignty in the aftermath of the COVID-19 pandemic.

1 Garnaut R (2014) Resolving Energy Policy Dilemmas in An Age of Carbon Constrains. The Australian Economic Review. DOI: 10.1111/1467 8462.12087.

2 Stanford J (2020) A Fair Share for Australian Manufacturing: Manufacturing Renewal for the Post-COVID Economy. The Centre for Future Work at the Australia Institute, <https://apo.org.au/sites/default/files/resource-files/2020-07/apo-nid307132.pdf>.

Roadmap objective and approach

Following the rationale set out above, the primary objective of this report is to identify opportunities to grow Australia's critical energy minerals sector and to connect mining activities with downstream manufacture by:

- assessing the energy technologies and underlying minerals expected to undergo accelerated growth as part of the energy transition (energy technologies and critical minerals shortlisted in the Roadmap are illustrated below)
- identifying the value-add opportunities across each of the related value chains
- setting out the commercial, regulatory and RD&D investment priorities required to realise these opportunities.

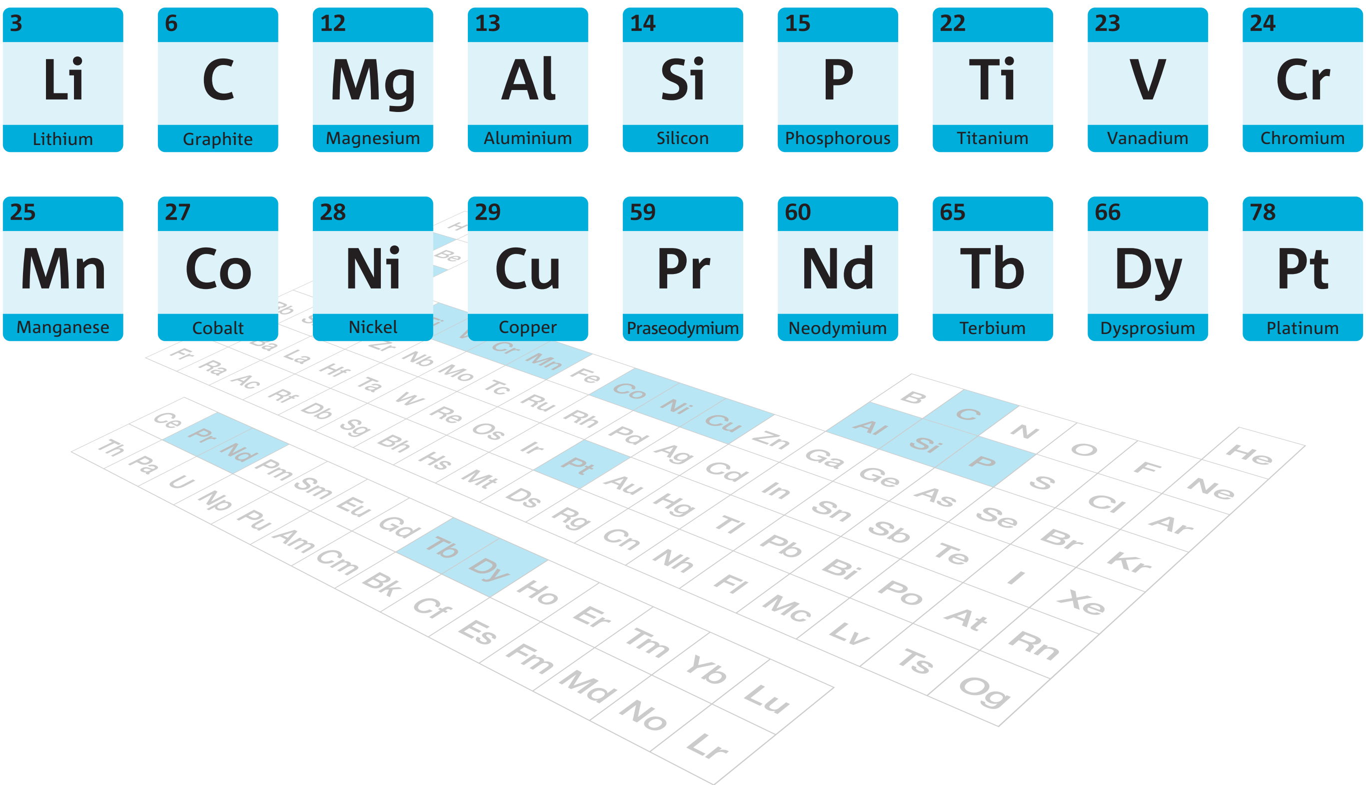
Energy technologies	
Generation	Storage
Solar PV	Batteries
Wind	Hydrogen (fuel cells and electrolysers)
Concentrated solar power	

Roadmap synthesis and summary of investment priorities

The emergence of critical energy minerals represents a unique opportunity for Australia to optimise the connection between its mining, manufacturing and energy sectors. **As the majority of the technologies expected to undergo accelerated growth rely on direct mechanical and electrochemical (as opposed to thermal) electricity generation, the key point of connection is in the production of high purity materials required to support the energy transition.** This represents a departure from mass production of lower purity metals for the steel sector which have dominated the mining industry to date. Investment in high purity materials is also likely to:

- improve access to finance for miners via stronger and more direct relationships with energy technology original equipment manufacturers (OEMs) and their suppliers
- create further synergies between processing operations (e.g. greater use of by-products)
- increase the scope for resource circularity via centralised metallurgical processing of both virgin and recycled materials
- help position Australia as a major global supplier of materials to a wide range of high-tech markets.

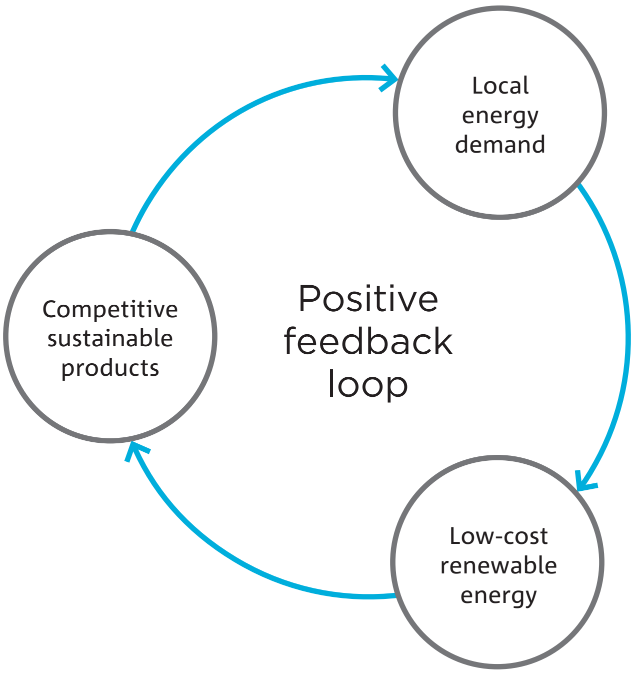
Critical energy minerals



In order to then move further downstream, several primary barriers arise in the Australian context:

1. **Customer location:** For most of the shortlisted energy technology value chains, production of high specification materials and their associated powders, alloys and components will require know-how and core intellectual property (IP) that exists in overseas jurisdictions. However, OEM decisions regarding technology licensing and investment in new regions is likely to depend on proximity to large consumer markets and the availability of dedicated R&D precincts to enable continuous improvement.
2. **High cost of energy:** Particularly on the east coast of Australia, the cost of energy continues to remain high which represents a barrier to cost competitive mining and manufacturing due to the price sensitivity of relevant processes.[3]
3. **Willingness to pay a premium:** The potential to supply sustainably sourced materials is a key comparative advantage for Australia. However, compliance with various sustainability measures and frameworks typically increases the cost of production. There is considerable conjecture over the willingness of OEMs to pay the consequent premium, particularly as they seek to levelise the cost of emerging energy technologies with fossil fuel incumbents.

However, there are a number of key enablers that have the potential to kickstart a positive feedback loop supporting local investment in Australia.



- **Local energy demand:** Although Australia's primary focus is on global energy technology supply chains, it is important not to underestimate the potential for local demand for renewable energy technologies in de-risking investment in domestic manufacturing. This includes the additional capacity required to support a potential renewable energy export industry (i.e. via energy carriers such as hydrogen). The most efficient mechanism to ensure the necessary investment is to implement staggered local content quotas that have an initial focus on scaling local manufacturing, followed by subsequent requirements on locally produced materials. This can also foster the development of dedicated R&D and manufacturing precincts.
- **Low-cost renewable energy:** The economies of scale expected to be achieved via local uptake of renewable energy technologies, particularly for energy export, is likely to place significant downward pressure on technology capital costs and the overall cost of energy.
- **Competitive sustainable products:** Integration of low-cost renewable energy is one of the primary means by which Australian mining and manufacturing proponents can produce sustainable outputs at a reduced premium. Given that the mining sector already represents 10% of Australia's total energy use, this could result in another material increase in local renewable energy demand.[4]

Solar Photovoltaics (PV)

The criticality of the underlying materials, comparative strengths on either end of the value chain and significant local demand creates considerable potential for a local solar PV manufacturing industry in Australia.

Upstream, there is increasing domestic activity in the development of high- purity-quartz (HPQ) deposits required to produce solar grade silicon metal. This is particularly important considering the current state of the global industry wherein two companies, both operating mines in the US, are responsible for the majority of the world's HPQ supply. Should local HPQ deposits be developed, an ambitious but important enabler of the upstream portion of the solar PV supply chain will be to vertically integrate extraction through to production of polysilicon (i.e. 9–11N purity silicon).[5] As a higher value intermediate product, production of polysilicon can help de-risk investment in local HPQ resources, promote longer term utilisation of recycled silicon and further the potential to supply other semiconductor markets.

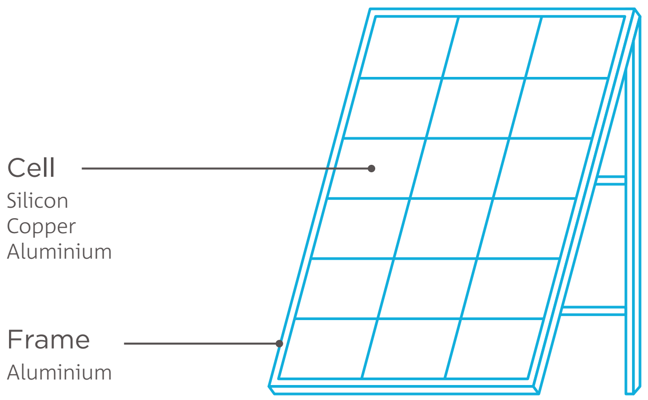
3 Australian Mining (2019) The Next Frontier. Minerals Council of Australia, Australia; Horne M and Reynolds C (2017) Energy costs and export competitiveness: evidence from Australian industries. Office of the Chief Economist, Australia.

4 SunSHIFT (2017) Renewable Energy in the Australian Mining Sector: White paper. ARENA, Australia.

5 99.9999999%–99.999999999% purity

Given the absence of an existing industry, polysilicon production is likely to require partnerships with established manufacturers overseas, integration of low-cost renewable energy and longer term development of production processes with a reduced energy and environmental footprint. Despite this, domestic polysilicon production is expected to command a premium over other low-cost jurisdictions which may adversely impact the subsequent competitiveness of locally manufactured wafers, cells and modules. The most effective way to reduce this premium is by leveraging Australia's leading capabilities in design of high efficiency solar cells and modules downstream to produce a competitive levelised cost of energy (LCOE).

Notwithstanding the scale of solar PV required to support a renewable energy export industry, local cumulative deployment in Australia is expected to be in the order of 100 GW by 2050. The imposition of local content quotas to support this level of deployment will therefore be a key enabler of investment in local manufacturing and ongoing RD&D.



Wind

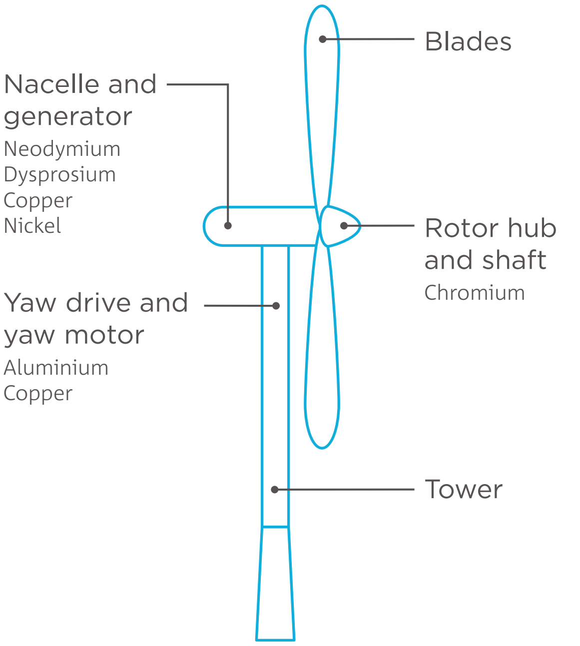
There is significant potential for Australia to develop domestic supply chains to support deployment of wind turbines. Of the discrete system components, while the generator shows the greatest potential to utilise Australia's critical minerals endowment, blades and towers also represent favourable opportunities for local manufacture.

The generator, which is one of most important system components in terms of performance, relies on the use of Neodymium-Iron-Boron (NdFeB) permanent magnets derived from rare earth elements (REE). However, wind turbines represent a comparatively small market for permanent magnets (compared to applications such as electric vehicle motors) and are therefore unlikely to be the primary driver for a domestic REE value chain.

This is particularly the case for the Australian market due to the likely roll out of '2-stage geared' turbines (onshore) as opposed to direct-drive turbines (offshore). The latter has a higher permanent magnet content but is more likely to see significant growth in Europe, Asia and the US.

While Australia is endowed with a rich supply of REE deposits and retains the technical capabilities needed to deploy local rare earth oxide (REO) separation facilities, it is industry concentration offshore and consequent price benchmarking that presents the primary barrier to investment. One of the more important means by which this can be overcome is through vertical integration of REE extraction through to the production of magnet metals. This will enable supply of a higher value product into a broader range of markets and increases the scope for centralisation of metallisation facilities (for virgin and recycled materials) to improve economies of scale. Beyond metallisation, permanent magnet production requires dedicated manufacturing facilities for wind generators (and electric vehicle motors) and investment in local production will require partnerships with major OEMs or third party suppliers.

Although not underpinned by critical minerals, there is also a unique opportunity to capitalise on leading Australian developments in advanced carbon fibre composites to further industry moves towards increased turbine blade lengths. Australia also retains the capacity to scale production of turbine towers which comprise primarily of low complexity steel.



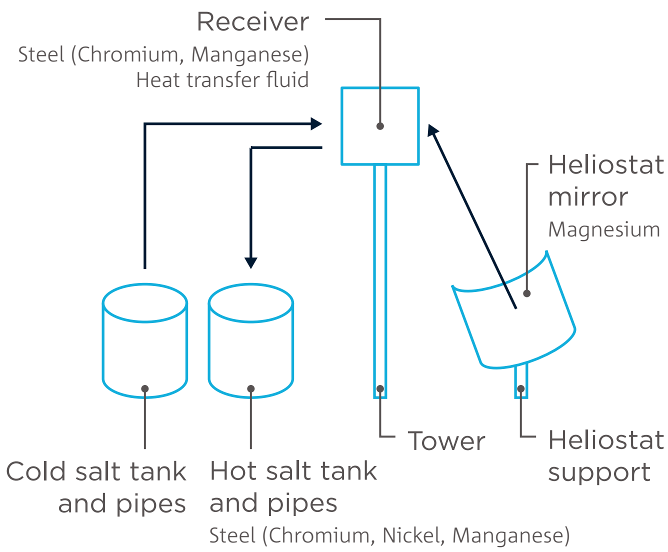
Concentrated Solar Power (CSP)

Australia is at the forefront of the emerging CSP industry. Increasing reliance on these systems for both electricity production and high-temperature process heat will enable greater opportunities to produce and export supporting high-value materials.

CSP, namely Central Tower configurations, are expected to become a more competitive form of renewable energy generation as greater value is placed on dispatchable (as opposed to variable) electricity generation. Increasing investment in the electricity sector is then likely to further the potential for integration of CSP in high temperature applications across a number of industries, including minerals processing.

CSP represents the only renewable energy technology (shortlisted in this report) that relies on thermal energy generation. As such, there is an ongoing requirement for lower purity metal alloys consisting of nickel, magnesium, manganese, vanadium and chromium. While Australia is a primary producer of some of these metals (e.g. nickel and manganese), there is currently limited local alloy production and that is unlikely to shift as a consequence of an emerging global CSP industry.

Rather, although not underpinned by critical minerals, IP key to the development of CSP plants relates primarily to the design of heliostats (i.e. sun concentrating mirrors) given the quantities required for a single asset and their impact on overall system cost. Emerging Australian companies are currently leading developments in this area through the optimisation of heliostat designs that can withstand harsh conditions with reduced volumes of material. CSP OEMs are likely to continue to commercialise their heliostat IP by partnering with local suppliers and manufacturers in Australia and overseas.



This is due to the poor 'packing density' and fragility of these units which makes them cost prohibitive to distribute.

However, Australia is currently leading development of thermal energy storage systems suitable for high temperature industrial processes that utilise phase change materials comprised of other critical minerals such as aluminium and graphite. Due to their broad operating range, these systems are particularly relevant to CSP as the industry moves towards higher processing temperatures (i.e. 800–1000°C). They are also modular and can be containerised and shipped offshore.

Batteries

Australia has significant potential to build capabilities across the battery value chain. Current efforts are ongoing to scale both the upstream and downstream portions separately which could lead to an integrated supply chain in the longer term.

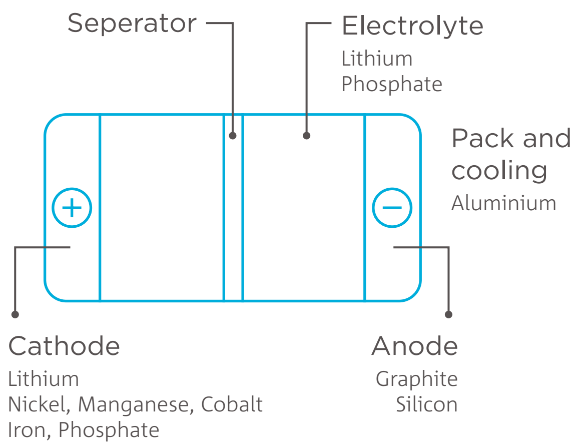
Upstream, Australia is a major producer of many of the primary raw materials (e.g. lithium, nickel and manganese) that underpin mature battery chemistries. The opportunity for vertically integrated production of electrodes (i.e. anodes and cathodes) will also likely see continued development of domestic cobalt, phosphorous, graphite and vanadium deposits despite more modest activity to date. Local production of electrode materials represents a significant opportunity to develop a higher value intermediate product that can increase supply chain diversity for global battery OEMs and further the potential for downstream battery manufacture in Australia.

One of the primary barriers to domestic manufacture however is that battery materials are subject to strict specifications and complex patents held offshore which can increase approval delays and costs for local proponents. For Australia to build competitive production facilities, strategic investment apportioned across both mature and emerging battery development is therefore likely to be required.

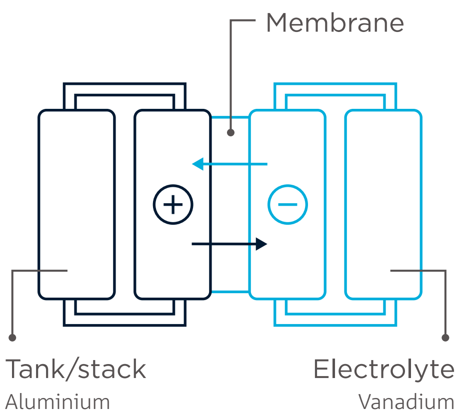
For mature battery chemistries, given the availability of the underlying materials within a proximate region, there is a unique opportunity to build battery hubs (for both primary production and recycling) and 'centres-of-excellence' to support ongoing development. Such initiatives can capitalise on existing efforts to develop certification labs, help attract international OEMs to set up operations onshore and commercialise battery cells and packs that are suitable for the Australian climate.

At the same time, to reduce long term dependency on global OEMs, there is also potential to increase R&D relating to next generation battery chemistries (e.g. lithium-metal). Despite smaller R&D budgets (compared to regions such as the EU and US), Australia has a strong precedent for developing step change improvements in mature battery technologies, as seen previously with the lead-acid 'Ultra-battery'.

Lithium ion



Vanadium redox



Hydrogen

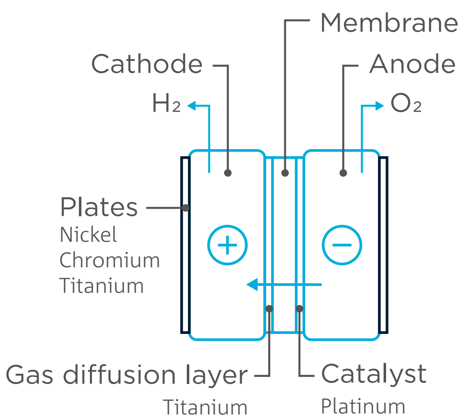
Compared to other energy technology value chains, the global hydrogen industry is relatively nascent. Consequently, there is considerable scope for Australia to ramp up investment in new supply chains, particularly in support of the opportunity to develop large-scale hydrogen export.

Fuel cells used in vehicles represent one of the more mature end-use applications for hydrogen with OEMs already deploying industrialised manufacturing facilities adjacent to emerging markets overseas. The challenge for local fuel cell manufacture in Australia is compounded by reliance on platinum as the primary critical metal due to limited domestic resources and the high cost of entry for platinum based catalyst production.

A different scenario presents in relation to electrolysis given that it underpins Australia's opportunity to export hydrogen and retain its role as a primary energy exporter through the energy transition. Export focused developments will also likely advance the potential for hydrogen use across domestic sectors such as transport. Of the mature forms of electrolysis, Proton Exchange Membrane (PEM) has the least established global supply chain which increases the scope for local manufacture in Australia. Alongside aerospace and defence technologies, PEM electrolysis could also provide another source of demand for locally produced titanium metal.

The key IP held by prominent PEM electrolysis OEMs relates to the integration of stack components. However, the underlying components are relatively easy to manufacture and partnering with these OEMs to deploy production facilities onshore can create new opportunities for local suppliers. Early engagement with OEMs would ensure PEM design specifications are suitable to the Australian climate and can promote ongoing R&D investment in titanium based additive manufacturing, low-cost catalysts and more durable components. Current efforts among OEMs to industrialise and automate stack manufacture will also help minimise the impact of higher Australian labour costs. Conversely, PEM electrolysis 'balance of plant' is typically 'off the shelf' and the imposition of local content quotas will likely ensure that demand is met by Australian manufacturers.

Electrolyser (PEM)



Summary of roadmap investment priorities

	Commercial	Regulatory/policy	RD&D
	General investment priorities		
Mining and processing	• Invest in mining operations that include downstream production of higher purity materials • Promote asset centralisation and synergies between adjacent processing operations • Pursue development of secondary minerals via joint ventures with junior and mid-tier miners • Improve assurance over ore deposits and flexible mining processes to fully exploit smaller critical mineral deposits • Improve access to capital by strengthening direct relationships with OEMs and their suppliers • Integrate mature low-cost renewable energy to help reduce premium for sustainable products	• Assist deployment of (non-mine specific) infrastructure (e.g. energy, transport) • Revise mine royalty regimes to include chemicals and alloys • Implement centralised research institutes to coordinate collaborations between industry and the research community • Improve tertiary training programs for production of high purity materials and chemicals • Incentivise greater exploitation of secondary minerals among major miners via joint ventures with junior miners • Ensure consistency of environmental and technical standards with key trading partners	• Increase RD&D in emerging spectroscopic ore sorting techniques to enable rapid in field testing and multimineral characterisation • Increase RD&D in 'sensor-based' ore sorting techniques (e.g. magnetic resonance) • Increase RD&D in in-situ mining and bioleaching methods for key critical minerals • Develop blockchain and geochemical fingerprinting to improve provenance tracking • Pursue metallurgical solutions (e.g. leaching and floatation) to process high value minerals in tailings • Continue to develop integration of high temperature renewable heat via CSP, hydrogen and biomass
Manufacturing	• Improve relationships with global OEMs to increase prospects for licensing of core IP and partnering to develop high specification materials and components • Pursue development of manufacturing precincts with coordinated research programs and collaborations • Pursue development of renewable energy export hubs (i.e. hydrogen or high-voltage direct current) adjacent to centralised manufacturing and recycling facilities	• Implement staggered local content quotas on manufactured products and underlying materials • Strengthen links between early stage R&D grant funding and local manufacturing to encourage commercialisation of IP onshore	• *As per value chain specific investment priorities*
Recycling	• Design energy technologies with reduced impurities that are easy to dismantle and recycle with low energy inputs • Encourage use of finance leases to improve knowledge of quantity, materials and recycling flows • Co-locate processing of virgin and recyclable materials • Implement hub-and-spoke models to reduce transport costs for centralised facilities	• Implement nationally consistent waste regulations (including uniform fees) • Implement robust product stewardship schemes that consider full technology lifecycles • Implement extended producer responsibility schemes • Consider potential for Asia-Pacific recycling hub development	• Increase RD&D in metallurgical processing technologies suitable for complex waste streams • Develop whole of system 'stocks and flow' models to inform optimised outcomes regarding recovery and use of critical minerals

	Commercial	Regulatory/policy	RD&D
	Value chain specific investment priorities		
Solar PV	• Increase development of HPQ resources and introduce globally recognised certification labs • Co-locate biomass feedstock alongside silicon metal production • Vertically integrate to polysilicon production	• *As per general investment priorities*	• Increase RD&D in polysilicon production process with reduced energy and environmental footprint (e.g. 'new silane' process) • Increase RD&D in cell manufacturing and in high efficiency cells and modules (e.g. perovskite and bifacial cells) • Develop efficient encapsulant separation methodologies
Wind (and EV motors as it relates to permanent magnets)	• Pursue vertical integration of rare earth metal production and deploy centralised production facilities for virgin and recycled materials	• Develop permanent magnet product stewardship by first targeting widely used electrical products (e.g. hard drives) to drive investment in recycling	• Increase RD&D in metallurgical methods such as flotation (e.g. froth floatation) to reduce the cost of REE extraction and separation • Increase RD&D in alternative solvents that minimise environmental impact associated with REE processing • Increase RD&D in innovative pyrometallurgical techniques and electrodeposition technologies to improve recycling of permanent magnets • Increase RD&D in carbon composite blades that enable more efficient recycling
CSP	• *As per general investment priorities*	• Implement CSP project pipeline to de-risk investment in local manufacturing	• Increase RD&D in thermal energy phase change materials by improving thermal conductivity • Promote engagement between CSP developers and metallurgical researchers to develop next generation alloys • Increase RD&D in 3D printing of superalloys for components such as solar receivers • Continue to integrate CSP in high temperature processing
Batteries	• Conduct further exploration and characterisation of graphite deposits to provide greater certainty over resources • Pursue vertically integrated cathode and anode active materials production • Develop battery hubs and centres of excellence within proximity to mineral resources	• Revise royalty programs to include battery precursors and active materials • Further develop product stewardship programs to include battery labelling, traceability & safety due to hazardous materials	• Increase RD&D in direct mineral to precursor processes (e.g. 'Direct Nickel' processing) • Further strategic investment in next generation battery research that aligns with Australia's comparative advantage where possible (e.g. lithium metal production) • Expand recycling processing research to encompass alternative battery chemistries, such as LFP and graphite anodes • Continue to develop electrolyte recovery and re-use • Improve pre-recycling processes such as sorting, classification and pre-treatment
Hydrogen	• Develop hydrogen export opportunities, utilising local titanium metal to de-risk investment	• *As per general investment priorities*	• Pursue development of continuous (as opposed to batch) processing and additive manufacturing (e.g. tape casting) to lower cost of titanium metal production as well as 3D printing of porous transport layers • Increase RD&D in alternatives to platinum catalysts • Increase RD&D in direct ammonia synthesis via electrolysis to support hydrogen export

Introduction

1 Report rationale

Why 'critical energy minerals'?

'Critical energy minerals' is an emerging theme that is explained by the convergence of two primary mining and energy sector trends. The first, 'critical minerals', represents a subset of minerals that are of growing concern due to potential supply risks and projected demand increases across a wide range of applications. These supply risks can include resource depletion, market concentration, environmental impact and political instability.[6] Criticality assessments are also dynamic and expected to change as consequence of geopolitical trends as well as new sources of supply and demand.

Separately, the transition to renewable energy represents the cornerstone of the global shift towards a low carbon economy and comprises of technologies that typically have a higher mineral intensity than incumbent fossil fuel energy assets.[7] While there are different degrees of maturity within the renewable energy portfolio, it is expected that most of these technologies will (or continue to) undergo accelerated growth over the coming decades.

This report seeks to explore the linkages between critical minerals and the renewable energy sector and therefore represents one input into a broader discussion on critical minerals in Australia.

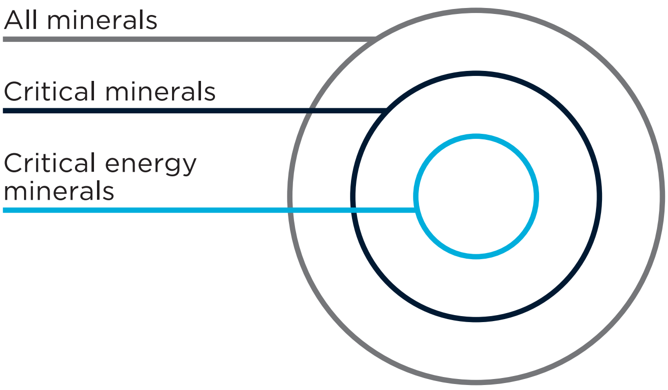


Figure 1: Critical energy minerals

Why Australia?

There are two primary factors unique to Australia that are driving further consideration of the nation's potential to derive value from critical energy minerals.

Firstly, at present Australia's economy consists of a large mining and comparatively small manufacturing sector. Specifically in relation to export, resources comprise 62% of total product versus manufacturing at 9%.[8] Importantly and in contrast to key trading partners in Asia and Europe, this reliance on the mining sector suggests that the emergence of critical energy minerals should be recognised as an opportunity to further capitalise on the nation's resource endowment. This includes diversifying Australia's export base and adding value through the manufacture of more complex products.

Secondly, Australia's access to renewable energy resources such as solar and wind, combined with land availability and a skilled workforce means that it has the potential to become a renewable energy 'superpower'.[9] When considered in conjunction with the rich endowment of relevant minerals and broad research, development and demonstration (RD&D) capabilities, Australia needs to also be localising manufacturing supply chains to support the expected global deployment of renewable energy systems. This will translate into higher productivity and an increase in direct as well as indirect employment via the emergence of ancillary supporting services.[10]

Why now?

The global market shifts currently occurring as a consequence of critical energy minerals makes it imperative for Australia to strategically invest in associated value chains. These market shifts are accelerating as countries and large global corporations continue to set net zero emissions goals to 2050 and look to establish supply chain sovereignty in the aftermath of the COVID-19 pandemic.

Further, while a number of the key renewable energy technologies have mature value chains, many are yet to hit a 'tipping point'. This creates considerable scope for investment in new regions. Similar opportunities exist for less mature energy technologies with comparatively undeveloped supply chains.

6 Graedel T et al. (2015) Criticality of metals and metalloids, PNAS. DOI: 10.1073/pnas.1500415112.

7 Hund K et al. (2020) Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition. World Bank Group, US.

8 Reserve Bank of Australia (2020) Composition of the Australian Economy: Snapshot. Viewed 4 November 2020, <https://www.rba.gov.au/education/resources/snapshots/economy-composition-snapshot/>

9 Garnaut R (2014) Resolving Energy Policy Dilemmas in An Age of Carbon Constrains. The Australian Economic Review. DOI: 10.1111/1467-8462.12087.

10 Stanford J (2020) A Fair Share for Australian Manufacturing: Manufacturing Renewal for the Post-COVID Economy. The Centre for Future Work at the Australia Institute, <https://apo.org.au/sites/default/files/resource-files/2020-07/apo-nid307132.pdf>

2 Analysis objective and approach

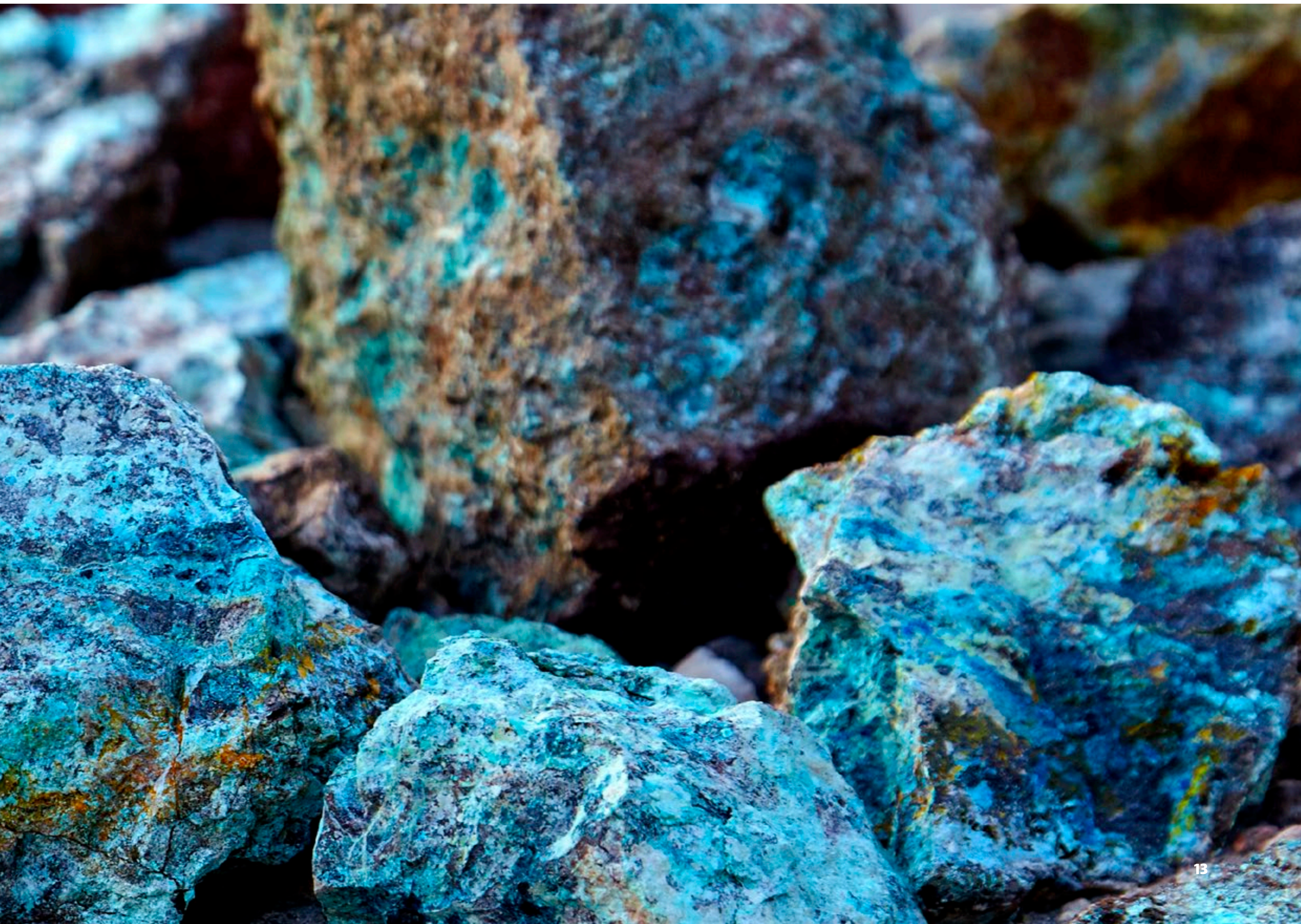
Following the rationale set out above, the primary objective of this report is to connect Australia's mining and manufacturing industries by identifying the critical minerals that will underpin the energy transition and the value-add opportunities that exist across each of the related value chains. This objective is achieved via the following two phases which are illustrated in Figure 2 and detailed below:

1. **Australia's critical minerals potential (Part I):** The first phase of the analysis identifies the technologies expected to undergo accelerated or exponential growth as part of the energy transition. Australia's potential to derive value from the critical energy minerals that underpin these technologies is then assessed. This assessment is then used as the anchor point to inform potential value-add opportunities in the subsequent phase of analysis.
2. **Value-add opportunities assessment and ecosystem development (Part II):** This section of the report assesses the potential for Australia to move up the value chains of the shortlisted energy technologies (i.e. beyond minerals extraction) to create new economic opportunities. It then sets out the investment priorities required to realise these opportunities. These investment priorities are categorised according to the following:
   - **Commercial:** Includes an assessment of the commercial considerations as well as business and financing models.
   - **Policy/Regulatory:** Includes an assessment of where policy is needed to stimulate relevant markets together with the technical/economic regulations that are required to facilitate deployment of relevant technologies.
   - **Research Development & Demonstration (RD&D):** Includes an assessment of where incremental improvements to mature technologies are needed as well as the potential for a selection of emerging technologies to provide the next wave of development. Demonstration projects needed to enable industry scale up are also considered.

Figure 2: Report assessment approach

Part I

Australia's critical energy minerals potential



1 Primary renewable energy technologies and underlying minerals

Figure 3 depicts cumulative global electricity demand to 2050,[11] highlighting those technologies expected to undergo accelerated growth as part of the energy transition. While similar growth curves are observed across a range of modelled scenarios, the actual installed capacities reflect the more ambitious target of global net zero emissions by 2050.

Figure 3a indicates that solar PV, wind and concentrated solar power (CSP) are the three primary electricity generation technologies expected to undergo accelerated growth to 2050. Given that solar PV and wind in particular are variable in nature, deployment of this form of energy generation will often require pairing with stationary storage. As shown in Figure 3b, batteries are the preferred storage solution for such applications.

Similarly, with the transition away from internal combustion engines (ICEs) in the transport sector, significant growth is forecast for electric vehicles (EVs) requiring either batteries (in GWh on left hand axis) and hydrogen fuel cells (in GW on right hand axis) as shown in Figure 3b. Note that electricity demand for hydrogen production and battery re-charging for EVs is also reflected in the total installed electricity capacity set out in Figure 3a.

However, in order to capture the consequent impact on minerals demand, a deeper analysis of the mature and emerging sub-technologies is required. Key technology trends relating to each are outlined in the subsections below. Further, although a significant increase in deployment of transmission and distribution infrastructure will be needed to enable the expected roll out of renewable energy systems, detailed analysis is beyond the scope of this report.

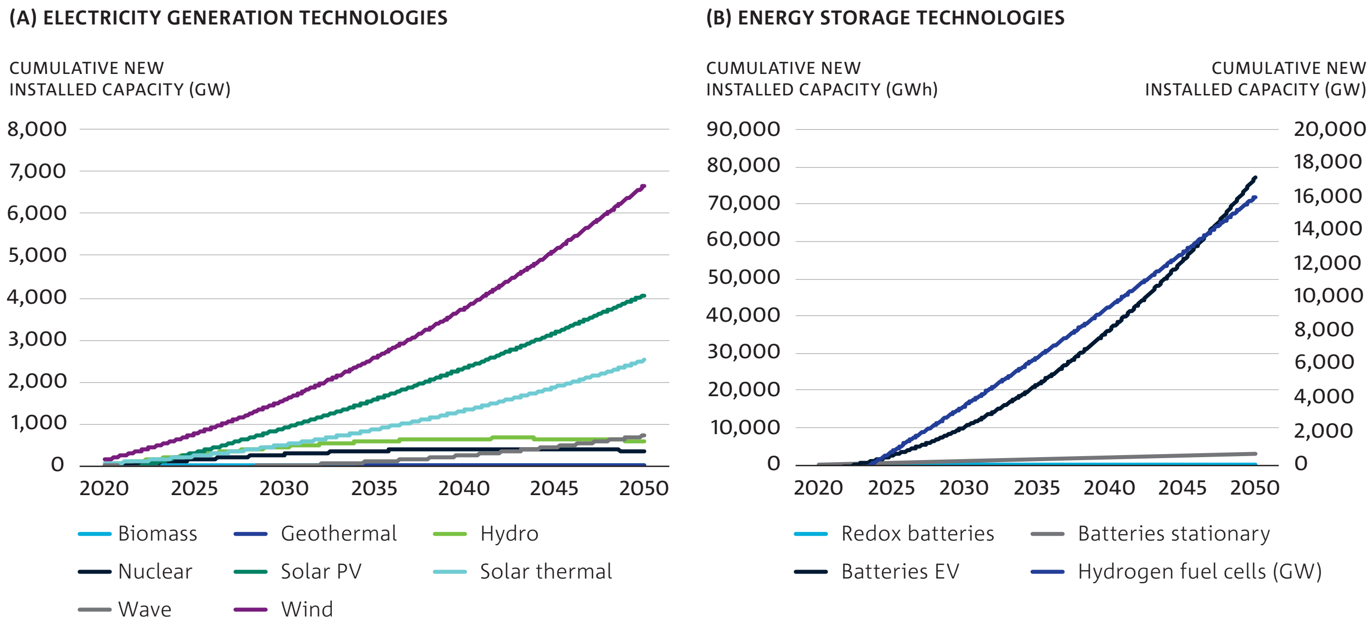


Figure 3: Projected global renewable energy installed (GW) to 2050

11 Electricity demand based on 'High VRE' scenario presented as part of the GenCost project undertaken by CSIRO and AEMO in December 2020. All energy demand numbers in the report are derived from this source unless quoted otherwise; Graham P et al. (2020) GenCost 2020–21: Consultation Draft. CSIRO, Australia.

Consideration of transmission and distribution (T&D) infrastructure

The transition to an electricity network with a high proportion of variable renewable energy (VRE) will mean more distributed utility scale sources of energy generation. Here, the output of individual assets is smaller than conventional thermal generation and asset location is restricted by the availability of a strong renewable energy resource. This is likely to lead to a material increase in the deployment of transmission and distribution infrastructure which consists primarily of steel, aluminium and copper.

Although detailed analysis of the demand for new T&D infrastructure is outside the scope of this report, it should not be overlooked in terms of the global supply risk and potential opportunities for Australia to supply the underlying minerals and components as part of the energy transition. Given the complexity associated with modelling demand for T&D, it is recommended as a follow on piece of analysis.

Solar photovoltaics (PV)

By 2050, solar PV could account for close to 30% of global electricity production. Crystalline silicon solar cells (C-Si), which currently comprise approximately 95% of total installations, are likely to continue to retain market share due to ongoing improvements in efficiency and cost.[12] This includes higher efficiency Passive Emitter and Rear Cells (PERC) which are displacing conventional Back Surface Field (BSF) cells. From 2018 to 2019, PERC's market share rose to more than 60% and is projected to completely displace BSF after 2024.[13] Although PERC is expected to remain the dominant technology, emerging heterojunction cells (combining crystalline and amorphous silicon film) are also expected to start gaining market share from 2025.[13]

Thin-film solar cell technologies, such as copper-indium-gallium-selenide (CIGS) and cadmium telluride (CdTe) currently make up 5% of the PV market.[12] While thin-film has demonstrated similar module efficiencies (to C-Si), particularly in geographies with low solar irradiance or in hot temperatures, it does not benefit from the same economies of scale in production and consequently has a higher capital cost.[14] The toxicity of some thin-film minerals (e.g. cadmium in CdTe) also pose health and environmental risks which could add to operating and end-of-life decommissioning costs.[15] Perovskite (and perovskite-silicon tandem) is another emerging solar cell which has shown significant promise due to its high efficiency and potentially lower cost of production (discussed further in Part II).

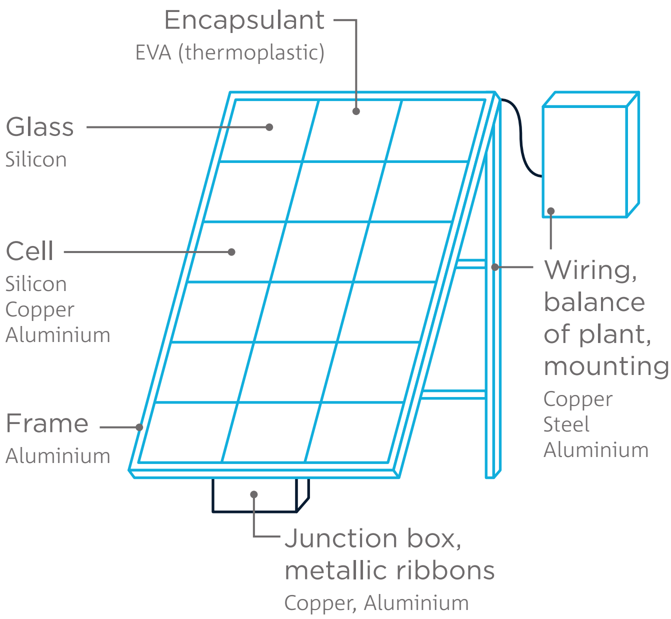


Figure 4: Summary solar PV materials

12 Particularly mono-crystalline silicon modules as opposed to multi-crystalline; Phillips S et al. (2019) Photovoltaics Report. Fraunhofer Institute for Solar energy systems, ISE.

13 BSF cells achieve an efficiency of roughly 20%, while PERC achieve roughly 24%, and heterojunction roughly 25%; VDMA (2020) International Technology Roadmap for Photovoltaic Results 2019, April 2020, <https://itrpv.vdma.org/>; VDMA (2019) International Technology Roadmap for Photovoltaic Results 2018. 10th Edition, March 2019.

14 Phillips S et al. (2019) Photovoltaics Report. Fraunhofer Institute for Solar energy systems. ISE; Lee TD et al. (2017) A review of thin film solar cell technologies and challenges. Renewable and Sustainable Energy Reviews. DOI: 10.1016/j.rser.2016.12.028.

15 Lee TD et al. (2017) A review of thin film solar cell technologies and challenges. Renewable and Sustainable Energy Reviews. DOI: 10.1016/j.rser.2016.12.028.

Wind

With over 650 GW installed worldwide, wind turbines are one of the most mature forms of renewable energy.[16] There are two types of turbines central to controlling generator speed relative to wind inputs; geared and direct-drive. The former converts the wind-dictated rotational speed of the rotor to a higher speed using a system of gears. Primarily deployed onshore, this turbine type accounted for approximately 80% of total global installed wind capacity in 2020.[17]

In direct-drive turbines, the turbine's rotor directly drives the generator, with no change in rotational speed. Here the turbines utilise neodymium-iron-boron (NdFeB) permanent magnet based generators to facilitate the direct conversion of wind inputs into electricity. Direct-drive turbines are primarily deployed in offshore environments due to reduced maintenance requirements compared with geared turbines which have a number of additional moving parts. Maintenance for offshore wind installations can have a significant impact on cost (compared to onshore installations) due to extended downtime periods as a result of wait times for specialised maintenance ships and weather constraints. Further, the absence of a gearbox in direct-drive turbines also enables better performance in higher-wind speed environments with reduced risk of fracturing the rotor.[18] Direct-drive is likely to benefit from ongoing investment, particularly due to its applicability to offshore wind which is forecast to increase from 38 GW in 2020 to 2,336 GW in 2050. This will be primarily driven by growth in regions such as Asia, Europe and North America.

While the industry had previously begun to move towards installation of direct-drive turbines onshore, there has since been a reversal of this trend with Goldwind now the sole major supplier of these turbines for onshore markets.[19] Part of the reason for this change is the price sensitivity of wind turbines to the cost of permanent magnets. For instance, it was found that a 100% price increase in rare earth elements caused up to a 41% increase in the cost of direct-drive turbines.[20]

This price sensitivity has also led OEMs such as Vestas and Adven to deploy turbines with a two stage gearbox and permanent magnet based generator that requires approximately 25% of the permanent magnet content (in direct-drive) and is suitable for mid-speed wind conditions.[21] Should these turbines eventually be able to tolerate higher wind speeds, they have the potential to displace direct-drive systems offshore.

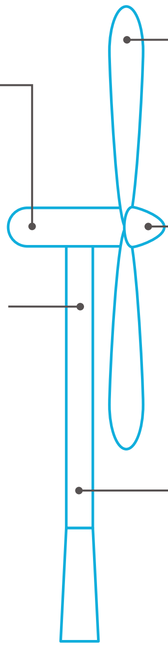


Figure 5: Summary of wind turbine materials

Concentrated Solar Power (CSP)

Parabolic trough and central tower (CT) represent the two main CSP configurations for electricity generation. Both technologies utilise conventional steam generators and an attached turbine to convert energy in the 'heat transfer fluid' (HTF) into electricity, but differ in relation to shape and design. While parabolic trough is comparatively mature and more widely deployed, its lower operating temperature (i.e. 290–390˚C) reduces overall efficiency which impacts performance.[22] Conversely, CT is less mature but is likely to be a more favourable form of electricity generation due to its comparatively higher operating temperatures (i.e. 290–565˚C).[22]

16 World Wind Energy Association (2020) Global Wind Statistics. Viewed 15 January 2021, <https://library.wwindea.org/global-statistics/>.

17 Hund K et al. (2020) Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition. World Bank Group, US.

18 Semken S et al. (2012) Direct-drive permanent magnet generators for high power wind turbines: benefits and limiting factors. IET Renewable Power Generation DOI: 10.1049/iet-rpg.2010.0191.

19 Serrano-Gonzalez J et al. (2016) Technological evolution on shore wind turbines – a market-based analysis, DOI: 10.1002/we.1974.

20 Leader A et al. (2019) The effect of critical material prices on the competitive of clean energy technologies. Materials for Renewable and Sustainable Energy, DOI: 10.1007/s40243-019-0146-z.

21 Pavel C et al. (2017) Substitution strategies for reducing the use of rare earths in wind turbines. Resources Policy. DOI: 10.1016/j.resourpol.2017.04.010.

22 Gonzalez-Roubaud E et al. (2017) Review of commercial thermal energy storage in concentrated solar power plants: Steam vs. molten salts. Renewable and Sustainable Energy Reviews, DOI: 10.1016/j.rser.2017.05.084.

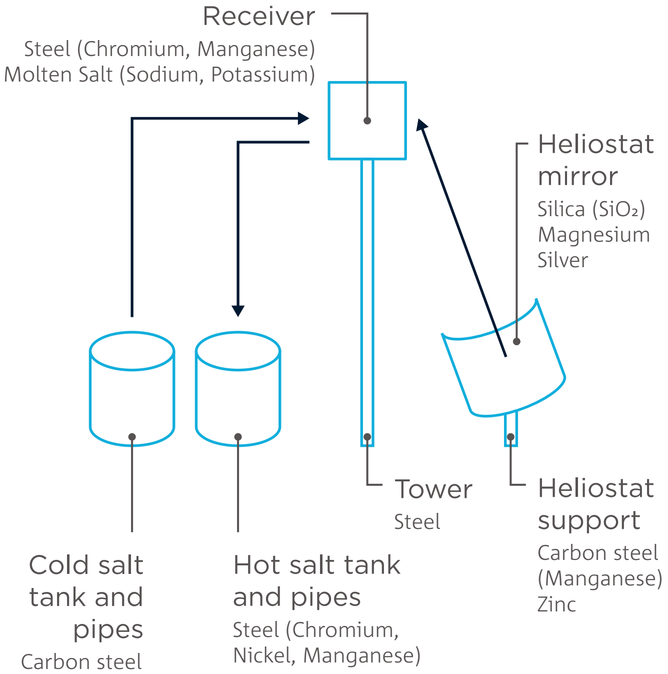


Figure 6: Summary of CSP CT materials

One of the primary challenges associated with CT is that it must be deployed at scale (i.e. greater than 100 MW) to be cost competitive. This has meant that CT requires a significant capital outlay (approximately 80% of total costs) and does not benefit from the learnings and gradual cost reductions that typically accompany scalable designs of other technologies such as solar PV.[23] This, combined with unfavourable electricity production tariffs (or power purchase agreements) has left a number of key projects unfinished, including in Port Augusta (South Australia) and Crescent Dunes (Nevada, US). This has served to negatively impact public perception of the technology and stifle ongoing investment.[24]

Other factors that have limited the deployment of CSP in recent years include its cost competitiveness with solar PV. However, unlike solar PV which is variable in nature, CSP is inherently dispatchable (or 'firm'), wherein the HTF can provide 6–14 hours of energy storage. Further, given that CSP relies on thermal generation and a spinning turbine, it also enables system inertia which is critical to maintaining grid stability via frequency control. As the proportion of VRE in electricity grids continues to increase, it is likely that there will be a premium placed on dispatchable energy which can help CSP become more competitive.[25]

Lastly, CSP has applications beyond electricity generation, which is a significant differentiator from other renewable energy technologies. The generation of thermal energy creates potential for high temperature applications across mining and processing of different materials (discussed further in Section 4.2.2 Part II). CSP is also expected to play a critical role in water desalination over the coming decades.[26]

Batteries

Lithium-ion batteries (LiB) represent the most mature and widely deployed battery type for stationary energy storage and EVs.[27] They are likely to retain global market share in the near and medium term (2030–2050) due to existing investment in large-scale manufacture, established technical knowledge as well as continued R&D in mature technologies and next generation battery chemistries.[28]

There are a number of variations within the LiB cathode chemistry itself that can have a significant impact on the underlying minerals demand. Lithium-nickel-cobalt-aluminium (LiNCA) and lithium-nickel-manganese-cobalt (LiNMC111 and NMC622) are among the more mature LiB cathodes used in both stationary and transport applications.[29] Until recently, LiNCA had been the primary choice of OEMs such as Panasonic and Tesla, with the latter using it in their original EV models. Recently however, the industry has indicated a preference for LiNMC batteries given that LiNCA is more costly and less stable.[30] Currently, efforts are ongoing to reduce overall cobalt content through the development of LiNMC811 cathodes which have a higher (8:1) ratio of nickel to cobalt.

23 IRENA (2012) Renewable Energy Technologies: Cost Analysis Series – Concentrating Solar Power Volume 1: Power Sector Issue 2/5.

24 Fedorowytsch T (2019) The future of solar thermal power once promised so much, but has the shine worn off?. 9 April. Viewed 15 January 2021, <https://www.abc.net.au/news/2019-04-09/has-the-shine-worn-off-solar-thermal-power/10983180>.

25 Rai A et al. (2020) Is there a value for "dispatchability" in the NEM? Yes. The Electricity Journal. DOI: 10.1016/j.tej.2020.106712.

26 Zheng Y et al. (2020) Concentrating solar thermal desalination: Performance limitation analysis and possible pathways for improvement. Applied Thermal Engineering. DOI: 10.1016/j.applthermaleng.2020.116292.

27 IEA (2020) Energy Storage – Tracking Report June 2020.

28 IRENA (2017) Electricity Storage and Renewables: costs and Markets to 2030. International Renewable Energy Agency; Edström K (2020) Inventing the Sustainable Batteries of the Future: Research Needs and Future Actions. BATTERY 2030+.

29 LiNMC batteries can have varied ratios of nickel, cobalt and manganese with each having different trade-offs in terms of cost and battery performance.

30 ATIC (2018) The Lithium-Ion Battery Value Chain: New Economy Opportunities for Australia; Ding Y et al. (2019) Automotive Li-Ion Batteries: Current Status and Future Perspectives. Electrochemical Energy Reviews. DOI: 10.1007/s41918-018-0022-z.

Another key LiB chemistry is lithium-iron-phosphate (LFP) which has been particularly prominent in China. Despite having a lower operating performance and energy density than LiNMC, LFP is cheaper, more stable and benefits from higher charge rates.[31] These batteries are expected to be deployed widely in the stationary storage market due to their safety, reliability and ease of maintenance. They are also becoming favourable solutions for mass market EVs. For instance, Tesla is intending to utilise LFP batteries for its upcoming Model 3 roll out in China.[32]

Longer term, next generation lithium-metal battery chemistries (e.g. lithium-air and lithium-sulphur) could disrupt the EV market. In these batteries, lithium metal is expected to replace graphite in the anode which will improve the operating performance and energy density. However, further R&D is required to overcome issues such as safety and stability.[33]

Other emerging battery chemistries such as sodium-ion could displace the use of lithium completely due to the relative abundance of sodium. However, these batteries have a lower energy density than LiBs and continued R&D in battery materials (in particular anodes) is required to achieve better electrochemical performance.[34] Zinc-air batteries are also being considered for the stationary storage market due to the abundance of zinc, safety characteristics and potential recyclability.[35]

Another of the more mature battery types which may continue to see increases in demand are vanadium redox flow batteries (VRFB). VRFBs consist of two liquid electrolytes that flow through porous electrodes separated by a membrane, through which electrons are transferred to produce electricity.[36] These batteries are expected to become cost competitive with LiBs for applications requiring energy storage of more than 4 hours and more than 300 cycles (i.e. utility scale applications).[37] Global uptake is being driven by China wherein several major VRFB developments are underway, namely the 200 MW/800 MWh battery in Dalian led by Ronke Power which is set for completion in 2020.[38] However their relatively low energy density is likely to render them unsuitable for the EV market.

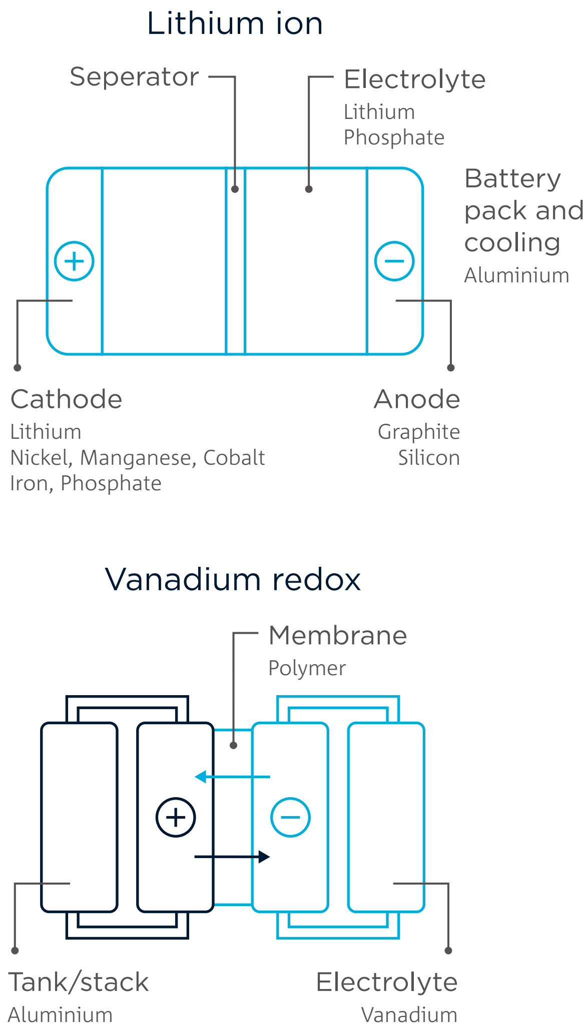


Figure 7: Summary of battery materials

Hydrogen

In recent years there has been a notable acceleration in the development of a clean hydrogen industry. This has been driven by a confluence of factors including technology maturity, significant reductions in the cost of renewable energy and the growing acceptance of its wide applicability as a clean energy carrier across applications in transport, heat and electricity generation.

31 IEA (2020) Global EV Outlook 2020 – Technology Report June 2020. IEA, France.

32 Staff (2020) Tesla to roll out China-made Model 3 cars with cobalt-free LFP batteries: sources. Viewed 18 January 2021, <https://www.reuters.com/article/us-tesla-china/tesla-to-roll-out-china-made-model-3-cars-with-cobalt-free-lfp-batteries-sources-idUSKBN26L26S>

33 Zhang X et al. (2018) Recent Advances in Energy Chemical Engineering of Next-Generation Lithium Batteries. Engineering. DOI: 10.1016/j.eng.2018.10.008.

34 Li L et al. (2018) Recent progress on sodium ion batteries: Potential high-performance anodes. Energy and Environmental Science. DOI: 10.1039/c8ee01023d; Perveen T et al. (2020) Prospects in anode materials for sodium ion batteries – A review. Renewable and Sustainable Energy Reviews. DOI: 10.1016/j.rser.2019.109549.

35 Hund K et al. (2020) Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition. World Bank Group, US.

36 Badwal SPS et al. (2014) Emerging electrochemical energy conversion and storage technologies. Frontiers in Chemistry. DOI: 10.3389/fchem.2014.00079.

37 Schmidt O et al. (2019) Projecting the Future Levelized Cost of Electricity Storage Technologies. Joule. DOI: 10.1016/j.joule.2018.12.008.

38 VSUN Energy (2019) Corporate Presentation, November 2019. Viewed 15 January 2021, <https://www.australianvanadium.com.au/wp-content/uploads/2019/11/VSUN-Energy-Presentation-November-2019.pdf>.

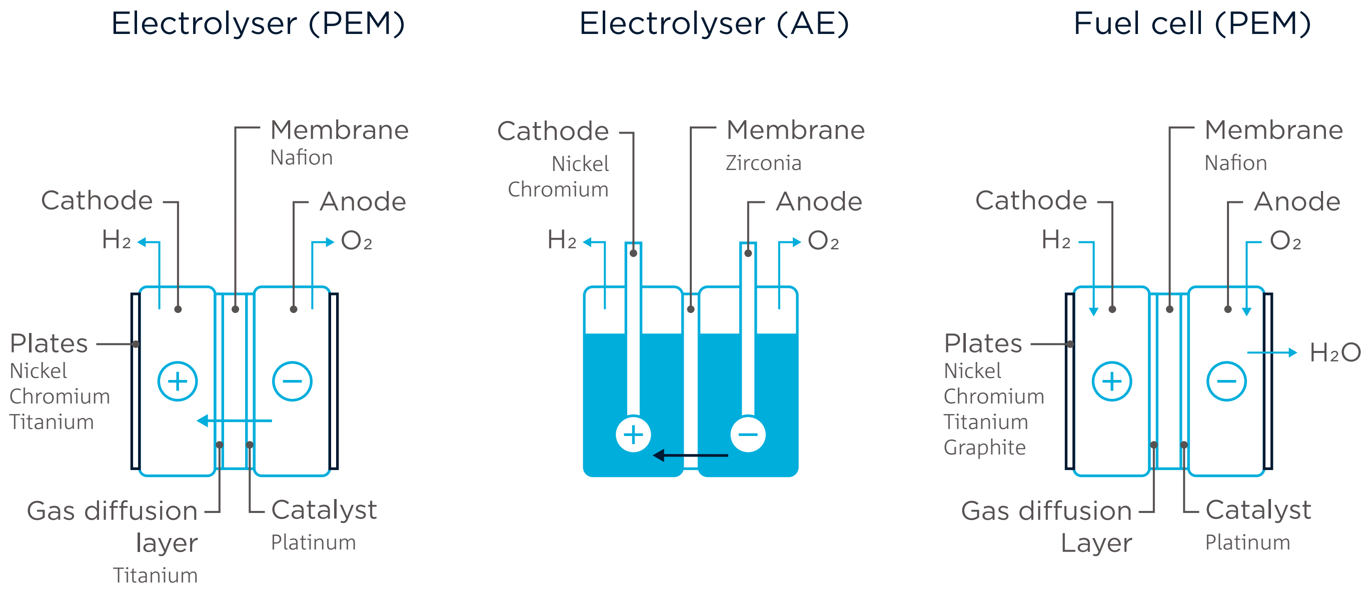


Figure 8: Summary of hydrogen materials

Longstanding markets for hydrogen (e.g. ammonia) have relied primarily on production via steam methane reforming of natural gas and may continue to do so as long as the CO_2 by-product is used or sequestered. Industry development however is being largely driven by cost and technological improvements in electrolysis, where hydrogen is produced via an electrical current (sourced from clean energy) to split water into hydrogen and oxygen, and fuel cells which utilise that hydrogen to produce electricity for both stationary and transport applications.[39]

Alkaline (AE) and Proton Exchange Membrane (PEM) are the more mature forms of electrolysis and offer complementary solutions depending on the specific application.[40] While solid oxide electrolysis (SOE) allows for the electrolysis of steam and therefore higher operating efficiencies, it currently has a number of challenges to overcome relating to durability of materials to extend system life. SOE also operates at temperatures between 700–800°C and may therefore be more restricted in its applicability due to the need for a source of waste heat to be cost competitive.

As is the case with batteries in EVs, vehicles are likely to be the dominant driver of demand for fuel cells. Given their high specific energy/power, low operating temperature and relatively high ramp rates, PEM fuel cells are likely to remain the preferred fuel cell technology for EVs and are continuing to benefit from cross-sector investment.[41]

Electric vehicle (EV) motors

While not explicitly modelled above, EV motors are a key enabler of battery and fuel cell uptake for transport purposes (i.e. for both battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs)). They also represent an important area of consideration given their reliance on NdFeB magnets which have a superior operating performance over 'electromagnets' used in conventional induction motors. Dysprosium is typically added to NdFeB magnets which enables it to operate at higher temperatures.[42]

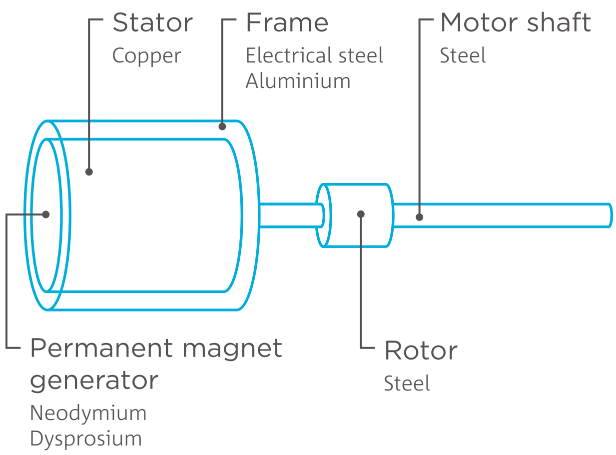


Figure 9: Summary of EV motor materials

39 CSIRO (2018) National Hydrogen Roadmap. CSIRO, Australia.

40 Guo Y et al. (2019) Comparisons between hydrogen production by alkaline water electrolysis and hydrogen production by PEM electrolysis. IOP Conf. Series: East and Environmental Science. DOI:10.1088/1755-1315/371/4/042022.

41 CSIRO (2020) Opportunities for hydrogen in commercial aviation. CSIRO, Australia.

42 Widmer J et al. (2015) Electric vehicle traction motors without rare earth magnets. Sustainable Materials and Technologies. DOI: 10.1016/j.susmat.2015.02.001.

2 Australia's potential to derive value from critical energy minerals

2.1 Critical energy minerals for the Australian context

Globally, a considerable amount of work has been undertaken to assess the 'criticality' of different minerals. A detailed assessment of critical minerals for Australia is therefore outside the scope of this report. Rather, given the potential economic opportunities that arise, mineral criticality is based on prior assessments made by Australia's key trading partners, namely the US, European Union (EU) and Japan. A shortlist of critical energy minerals is set out in Figure 10.

Specifically, minerals were deemed critical for the purposes of the report if widely recognised as critical among key trading partners for all sectors and also expected to be in high demand due to the energy transition (Tier 1). Accepting the subjective and dynamic nature of criticality, minerals that were not as widely considered critical by Australia's key trading partners but likely to become so in light of the energy transition were also included (Tier 2). The same is true for minerals widely considered critical but not expected to face high demand as part of the energy transition. Expected volumes of minerals required are also set in Appendix A.

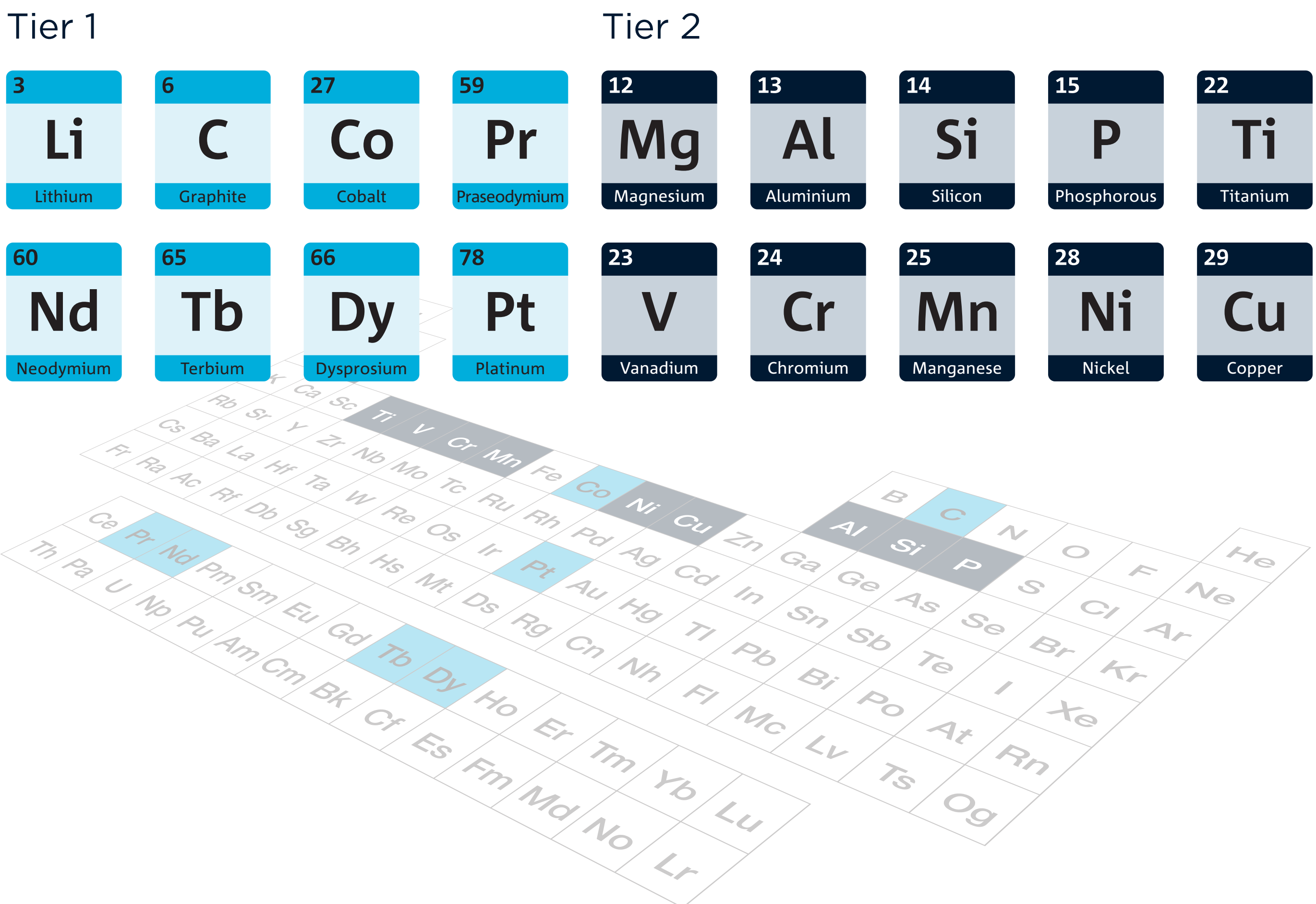


Figure 10: Summary of critical energy minerals

2.2 Critical energy minerals opportunity assessment

Assessing Australia's potential to derive value from critical energy minerals is a complex process. While consideration of reported local resources provides an important starting point, reliance on these figures alone can lead to an oversimplification of the analysis due to changing global market conditions, project economics and discovery of new deposits. This section therefore highlights some of the dominant trends and market shifts occurring for each of the shortlisted critical energy minerals (summarised in Table 1) and the consequent opportunities and risks for Australia.

Key findings from the opportunity assessment of the shortlisted critical energy minerals are set out in Table 2. A more detailed assessment may be found in Appendix B.

Table 1: Trends that highlight Australia's critical energy minerals potential

Trend	Explanation
Local economically demonstrated resources (EDR) and production	Captures (EDR) and existing local production from 2019. All local and global EDR and production numbers have been sourced from Geoscience Australia's 'Australia Identified Minerals Resources Report' unless stated otherwise.[43]
Criticality and global competition	Considers supply chain risk and the consequent geopolitical trends that increase scope for Australia to develop or expand development of a particular mineral.
Local sustainability	Considers any local trends relating to a particular mineral that may prevent extraction or materially impact social licence to operate.
Demand	Considers technological developments in the energy sector that could lead to substitution of a given mineral and consequent investment risk to local suppliers.

43 Senior A et al. (2021) Australia's Identified Mineral Resources 2020. Geoscience Australia, Australia.

Table 2: Critical minerals assessment

	Local resource	Local production
Aluminium	Aus holds 18% (5,292 Mt) of global bauxite EDR.	Aus produced 28% of the world's bauxite ore in 2019, but only 15% of global alumina and 3% (1,570 kt) of aluminium.
Chromium	Aus holds 534 kt of chromite EDR.	Currently no local chromium production.
Cobalt	Aus holds 19% (1,399 kt) of global EDR. Mostly a by-product of nickel with relatively low concentrations. The highest cobalt with nickel associations are found in lateritic ores which remain expensive to process.	Aus produced 4% (5,700 t) of global cobalt in 2019.
Copper	Aus holds 11% (93,356 kt), 2nd highest in global EDR.	Aus produced 5% (938 kt) and ranked 6th in global production of copper in 2019.
Graphite	Aus EDR reported at 7,968 kt but some uncertainty. Typically smaller deposits compared to those found in Africa.	Currently no local natural graphite production.
Lithium	Aus holds 29% (5,702 kt) of global EDR. Typically hard rock spodumene.	Aus produced 56% (45 kt) of global lithium in 2019.
Magnesium	Resources are abundant and globally dispersed.	Majority of Aus production (413 kt) is low purity products.
Manganese	Aus holds 14% (114,000 kt) of global EDR.	Aus produced 17% (3,185 kt) of global manganese in 2019.

Criticality and global competition	Local sustainability	Demand/substitution risk
Energy technologies unlikely to strain aluminium resources. China holds 3% of global bauxite EDR but produces more than 50% of the world's alumina and aluminium which increases scope for diversification. Lower energy costs needed for Aus to produce aluminium competitively.	High energy intensity.	Reduced substitution risk due to abundance of aluminium. Recycling may reduce demand from primary production.
Energy technologies unlikely to strain global chromium EDR. South Africa produces 39% of global chromium. Labour and electricity costs, unreliable electricity supply and depletion of surface level deposits in South Africa may open new opportunities for other producers but significant infrastructure investment required for Aus.	No notable high risk sustainability challenges.	Demand for chromium is primarily driven by the stainless steel market. Unlikely to be impacted by energy technologies specifically.
Energy technologies alone are expected to place significant strain on global EDR (i.e. 7,188 kt global EDR vs 7,125 kt cumulative 2050 demand from energy technologies). Democratic Republic of Congo (DRC) currently holds 50% of EDR and is responsible for 70% of production but ranks poorly in political stability and sustainability metrics. Battery OEMs pushing for diversification away from DRC. Prospective projects in Aus for higher content cobalt in copper/gold deposits (e.g. Cobalt Blue).	No notable high risk sustainability challenges.	Short term risk is low due to existing investment in LiNMC (111 and 622). Longer term potential to reduce (or remove) cobalt content although some uncertainty over LiNMC811.
Global copper EDR reported at 877,356 kt (vs 130,931 kt cumulative 2050 demand from energy technologies). T&D infrastructure, EVs and other copper dependent industries will likely place a strain on copper supply. Copper refining is increasingly concentrated in China. Mainly underground mines in Aus provides a comparative advantage as surface level deposits deplete globally.	No notable high risk sustainability challenges.	Used across most energy technologies. Potential for aluminium to substitute for some electrical equipment and power cables but with reduced performance.
Global EDR are 307,868 kt (vs 82,519 kt cumulative 2050 demand from energy technologies). China currently produces 60% of all graphite (synthetic and natural) and is responsible for processing all of the world's graphite for LiBs. Scope for more strategic diversification by battery OEMs and a series of prospective projects in Aus.	No notable high risk sustainability challenges.	Current uncertainty over demand for natural as opposed to synthetic graphite (higher emissions but reduced purities enabling better performance). Longer term potential for substitution in LiBs via emerging silicon and lithium metal anodes.
Global EDR likely to exceed cumulative demand from energy technologies (8,990 kt to 2050) but production rates could result in supply bottlenecks. Global production in 2019 was 80 kt. Aus is well placed to manage demand uncertainty as spodumene has a higher lithium content and quicker ramp-up rate than brine deposits in South America.	High waste. 30–50% of lithium is lost in production of lithium concentrate.	Low substitution risk given expected dominance of LiBs in the near and medium term.
Concentration risk stems from China being responsible for 82% of global magnesium metal production. Opportunity for Aus to increase production but not likely to be driven by energy technologies.	No notable high risk sustainability challenges.	Demand is primarily driven from metal alloys used in other industries and this is likely to continue.
China imports the majority of the world's manganese ore to produce manganese products. Scope for Aus to ramp up production with increase demand from energy tech (20,913 kt cumulative demand to 2050) via emerging companies such as Element 25.	No notable high risk sustainability challenges.	Likely greater use in LiNMC battery cathodes due to importance in reducing thermal runway. Manganese may also be used in next generation lithium metal batteries (albeit at lower volumes).

	Local resource	Local production
Nickel	Aus holds 24% (21 Mt) of global EDR.	Aus produced 6% (155 kt) of global nickel in 2019.
Phosphorous	Aus holds less than 2% (1,091 Mt) of global phosphate rock EDR.	Sole Aus producer is Incitec Pivot, Qld.
Platinum	Modest Platinum Group Elements (PGE) EDR (37.6 t). Low volumes in primary deposits may not warrant extraction.	Currently no local production.
Rare Earth Elements (REE)	Aus has 6th highest economic EDR (4,030 kt).	Aus produced 8% (17.7 kt) of global REEs in 2019 but currently no commercial downstream processing.
Silicon (High Purity Quartz)	High purity quartz (HPQ) (>99% purity) required for solar PV is scarce (c.f. lower purity quartz used for glass and construction). A number of prospective HPQ deposits in Aus.	Currently no local HPQ production.
Titanium	Aus possesses 24% (165 Mt) of global ilmenite and 65% (33.6 Mt) of global rutile EDR.	Aus currently produces titanium dioxide (TiO_2) for use in paints but is not an active producer of titanium sponge metal.
Vanadium	Aus possesses 25% (6,019 kt) of global EDR.	Aus is not an active producer but there are several prospective projects.

	Criticality and global competition	Local sustainability	Demand/substitution risk
	Global EDR were 90 Mt (vs 48 Mt cumulative 2050 demand from energy technologies). Requires ramp-up production of battery grade nickel to service the battery market. Production is globally dispersed. Global depletion of sulphide deposits means increased reliance on laterite deposits (complex compositions and more costly to process).	Increased energy and chemical intensity with growing global reliance on laterite ores.	Trends towards greater nickel content in the battery sector (and reduction of cobalt) e.g. 8:1 ratio of nickel to cobalt in LiNMC811 batteries.
	Criticality stems from reliance on phosphorous in fertilisers rather than energy technologies. Primary producing countries are China, US and Russia, but further depletion could lead to increased reliance on Morocco and Western Sahara which hold 72% of global EDR. Opportunity for Aus to divert some local production to LFP cathodes.	No notable high risk sustainability challenges.	Comparatively low volumes required for LFP batteries and $LiPF_6$ electrolyte. Limited substitutability risk.
	Concentration in countries with sovereign risk. South Africa holds 91% of global PGE EDR and 72% of global platinum production. Russia and Zimbabwe are also significant producers. Platinum demand from fuel cells higher than combustion engines which may create new market opportunities. Potential for Aus likely dependent on extraction as a by-product of nickel, copper, chromium and uranium.	No notable high risk sustainability challenges.	Some degree of substitutability in fuel cells with palladium but likely to be a blended catalyst due to co-extraction.
	Concentration in China for mining and downstream processing of REEs to permanent magnets. China is able to set the benchmark on REO price due to this concentration. Strategic investment required to establish REE value chain in Aus.	Cracking and leaching of REO produces low level radioactive waste. Energy and water intensive processing.	Low degree of substitutability of permanent magnets in EVs (due to efficiency and vehicle weight). Industry shifts to 2-stage geared offshore wind turbines can reduce REE demand.
	Growing pressure for high purity silicon products from the solar PV and semiconductor markets. HPQ production is opaque and concentrated in two US mines. Downstream production of high purity silicon metal products is concentrated in China. Opportunities for Aus to develop HPQ industry should prospective deposits be realised.	No notable high risk sustainability challenges.	Crystalline silicon will likely remain the predominant solar PV technology. Also continued demand from electronics sector and potentially battery anodes.
	Increasing pressure for titanium metal for defence and aerospace applications. Demand unlikely to be shifted by energy technologies. Kroll process for titanium production is high cost with high barriers to entry due to downstream integration in China (40%), Japan (26%) and Russia (21%).	Some resources unavailable due to coastal location and competing land uses.	Low substitutability risk in PEM electrolysers due to requirement for corrosion resistant materials.
	Dominant producers are China (55%) and Russia (25%) and uncertain growth in demand from the steel sector. Unlikely to be impacted by energy technologies. Potential for Aus to ramp up supply under the right market settings. Two prospective projects under development.	No notable high risk sustainability challenges.	Likely dependent on uptake of VRFBs against other battery technologies.

2.3 Summary of Australia's critical energy minerals potential

Australia has significant potential to derive value from the shortlisted critical energy minerals. However, despite its endowment, there is likely to be a real resources constraint (e.g. greenfield exploration, infrastructure, skilled workforce) that will require careful consideration of investments. Figure 11 therefore seeks to help prioritise investment by comparing the potential value of each opportunity (based on 2050 global demand from the energy transition only and market price of each metal), against the associated investment risk for Australia (assessed in Section 2.2). Noting the expected volatility in supply and demand for a number of these critical minerals, the market value of each is based on the average traded price of the metal over the last 5 years. All supporting assumptions can be found in Appendix A and B.

Despite their comparatively lower unit price, major minerals such as nickel, copper and aluminium represent some of the highest value opportunities from the energy transition due to the volumes required. As an established supplier of these minerals, this is likely to require a renewed focus on improving infrastructure (e.g. energy), uncovering economic deposits and investment in downstream processing which can help Australian proponents access energy technology supply chains (discussed further in Part II). A similar theme applies to manganese, magnesium, and lithium despite their comparatively smaller markets.

Other minerals such as silicon, chromium and cobalt represent high value opportunities notwithstanding their comparatively low volumes. Notably however, despite Australia's resource potential, they are higher risk opportunities due to some uncertainty regarding longer term demand and/or global competition relating to extraction and processing. Similarly, the next group of minerals in terms of market size (i.e. platinum, REEs and graphite) are likely to require considerable capital investment given minimal local activity to date and existing barriers to market. In many cases, and particularly due to distorted markets overseas or price volatility, investment in these higher risk minerals may be driven by strategic supply chain priorities as opposed to clear commercial opportunities.

For titanium, phosphorous and vanadium, with a smaller return on investment from the energy sector specifically, their development in Australia is likely to be dependent on investment from alternative sectors.

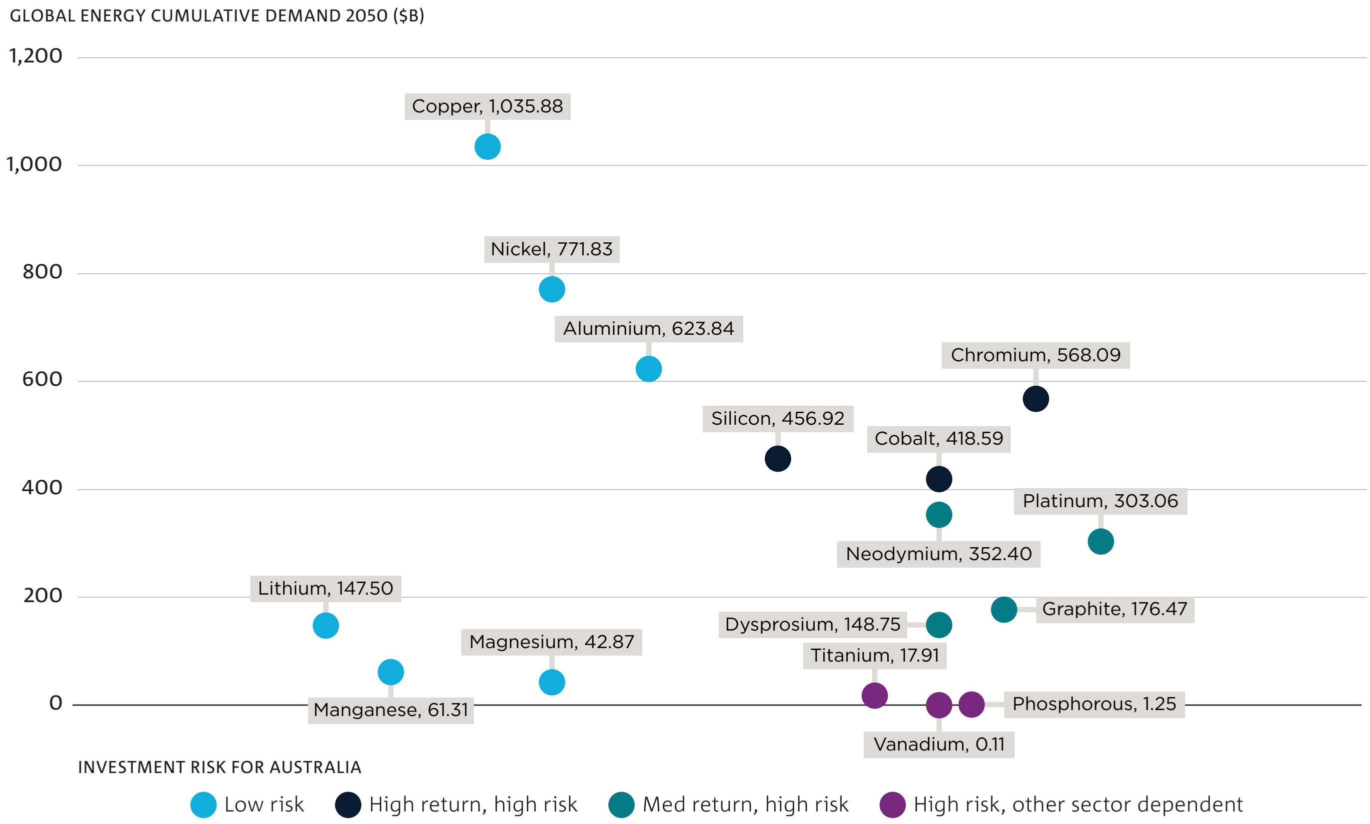
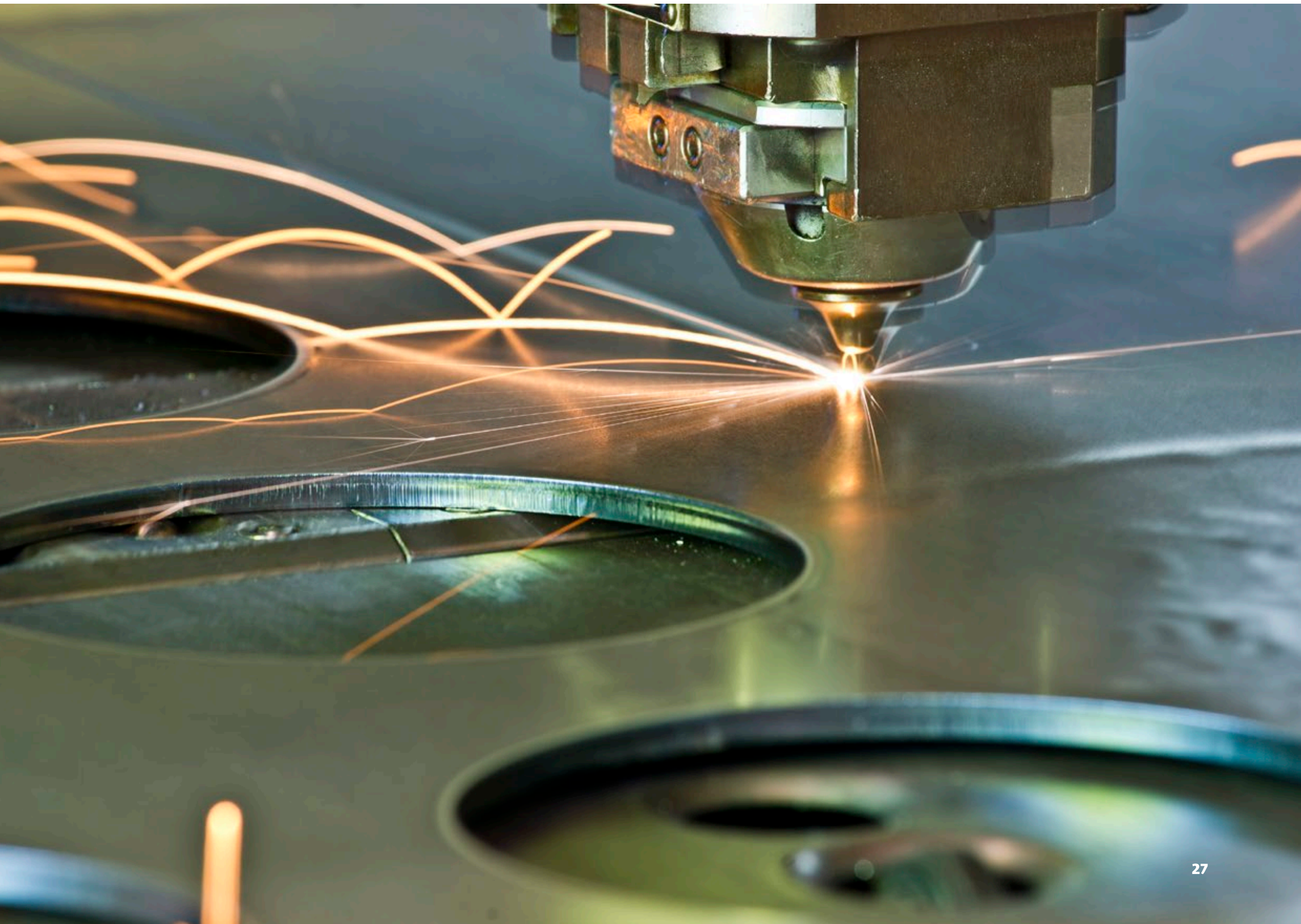


Figure 11: Summary of critical energy minerals opportunities

Part II

Supply chain analysis



1 General considerations and investment priorities

This section of the report summarises the general considerations and investment priorities (i.e. commercial, regulatory and RD&D) that exist across each of the shortlisted minerals and energy technologies. They are divided according to the three primary value chain steps, namely: 'mining & processing', 'manufacturing' and 'recycling'. Note that RD&D priorities relating to manufacturing are specific to each value chain and therefore not included in this section.

1.1 Critical energy minerals mining and processing

1.1.1 Commercial

Industry nascency

Despite the maturity of Australia's mining sector, the modest levels of activity observed in relation to a number of shortlisted critical energy minerals (refer Figure 11 Part I) represents an opportunity to improve the existing industry. Production of higher grade materials as well as efficient mining of secondary minerals and smaller deposits represent three primary ways in which this may be achieved.

Refined and high purity materials

Many of the energy technologies expected to undergo accelerated growth as part of the energy transition rely on direct-mechanical and electrochemical (e.g. solar PV and fuel cells) as opposed to thermal (e.g. gas-fired) electricity generation. These energy technologies typically require high purity materials, production of which would represent a departure from Australia's existing 'dig and ship' supply of lower purity materials for the steel sector.

Refined materials enable the sale of higher value products to a broader range of customers within and outside of the energy sector, including trading houses in Japan and Korea who are investing in more 'mid-stream' processing globally. It also increases scope for deployment of centralised metallurgical processing facilities that can accept both virgin and recyclable materials and enables greater use of by-products that can feed into adjacent supply chains. For instance, production of sulphur dioxide from copper metal production can be leveraged to synthesise various metal sulphate precursors for the battery market.[44]

Further, in contrast to major minerals such as iron ore, many of the shortlisted critical minerals (e.g. vanadium and platinum) typically have relatively low ore concentrations. This creates additional incentive for proponents of these minerals to process locally in order to produce higher value materials and reduce transport costs.

Mining of secondary minerals

While drilling and ore characterisation typically provides a comprehensive analysis of the ore, mining companies have traditionally focused on gathering enough information to optimise extraction of primary minerals, with less regard for secondary products. As a consequence, this has often led to valuable commodities ending up in mine tailings despite their critical nature and potential value.

To improve this, wider reporting of co-products can increase the scope for joint ventures between mining companies to co-develop different minerals from the same deposit (which can improve access to capital discussed further below). Figure 12 shows the co-location of primary and secondary minerals in Australia and depicts where simultaneous extraction requires integrated/complementary processing technologies (e.g. direct-acid leaching and particle size sorting) versus complex additional processing (e.g. multi-stage solvent extraction).

44 Memary R et al. (2012) Life cycle assessment: a time-series analysis of copper. Journal of Cleaner Production. DOI: 10.1016/j.jclepro.2012.04.025.

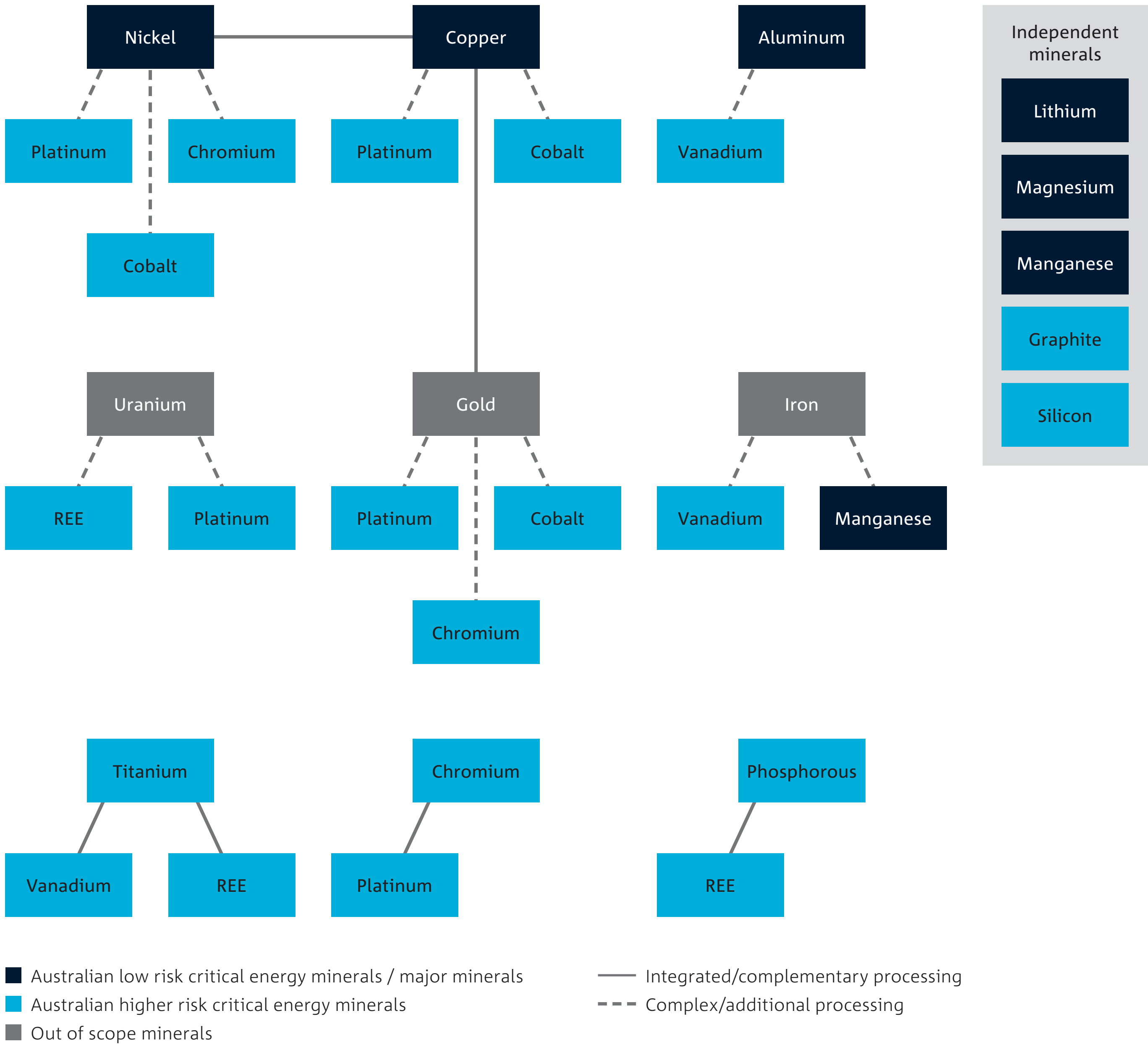


Figure 12: Shortlisted major minerals and ease of extraction of secondary minerals[45]

45 Nickel – Crundwell F et al. (2011) Extractive Metallurgy of Nickel, Cobalt and Platinum Group Metals. Elsevier, The Netherlands; Mudd GM et al. (2013) Quantifying the recoverable resources of by-product metals: The case of cobalt. Ore Geology Reviews. DOI: 10.1016/j.oregeorev.2013.04.010; Dzinamurungu T et al. (2020) A Process Mineralogical Evaluation of Chromite at the Nkomati Nickel Mine, Uitkomst Complex, South Africa. Minerals. DOI: 10.3390/min10080709. Copper – Ayres RU et al. (2002) The Life Cycle of Copper, its Co-Products and By-Products. Mining, Minerals and Sustainable Development, France. Aluminium – Gomes HL et al. (2016) Vanadium removal and recovery from bauxite residue leachates by ion exchange. Environmental Science and Pollution Research. DOI 10.1007/s11356-016-7514-3. Uranium – Mudd GM (2018) Global platinum group element resources, reserves and mining – A critical assessment. Science of the Total Environment. DOI: 10.1016/j.scitotenv.2017.11.350; Zhu Z et al. (2015) Separation of uranium and thorium from rare earths for rare earth production – A review. Minerals Engineering. DOI: 10.1016/j.mineng.2015.03.012. Gold – Mpinga C et al. (2015) Direct leach approaches to Platinum Group Metal (PGM) ores and concentrates: A review. Minerals Engineering. DOI: 10.1016/j.mineng.2015.04.015; Adams MD (2016) Gold Ore Processing: Project Development and Operations. Elsevier, The Netherlands. Iron – Moskal RR et al. (2003) Processing of vanadium: A review. Minerals Engineering. DOI: 10.1016/S0892-6875(03)00213-9; Zhang Y et al. (2017) Separation and recovery of iron and manganese from high-iron manganese oxide ores by reduction roasting and magnetic separation technique. Separation Science and Technology. DOI: 10.1080/01496395.2017.1284864. Titanium – Taylor PR et al. (2006) Extractive metallurgy of vanadium containing titaniferous magnetite ores: A review. Minerals & Metallurgical Processing. DOI: 10.1007/BF03403340; Haque N et al. (2014) Rare Earth Elements: Overview of Mining, Mineralogy, Uses, Sustainability and Environmental Impact. Resources. DOI: 10.3390/resources3040614. Chromium – Cawthorn RG (2010) The Platinum Group Element Deposits of the Bushveld Complex in South Africa. Platinum Metals Review. DOI: 10.1595/147106710X520222; Nassar NT et al. (2015) By-product metals are technologically essential but have problematic supply. Science Advances. DOI: 10.1126/sciadv.1400180.

Smaller deposits

A common practice within the Australian mining sector has been to establish large operations and increase production margins via improved economies of scale.[46] Consequently, prospective projects are typically capital intensive and high risk. There has also been a general aversion to mining of smaller deposits due to high permitting, exploration and capital costs which are unable to be properly amortised due to shorter mine lives.

However, the nature of many of the shortlisted critical energy minerals is that they often exist in smaller deposits. Vanadium for instance, is often found in sandstone-hosted deposits ranging in size from 1 to 10 Mt.[47] This is an order of magnitude smaller than iron ore deposits which generally range between 200 to 500 Mt.[48]

The Australian mining industry may therefore need to improve the economics of extraction for smaller deposits. Improved assurance over ore deposits represents a key starting point. For instance, although rigorous ore characterisation may prolong mine feasibility studies, it can allow mining companies to commence development of smaller mines at the lowest marginal cost. This can be aided by greater collaboration with the Australian research sector (discussed further in Section 1.1.2).

Smaller operations also allow for further integration of renewable energy (discussed below) as well as more modular and flexible operations which can be switched on and off to improve the commercial viability of more modest deposits.[49] This has been demonstrated recently by the IMP@CT project in Europe.

Case Study: IMP@CT Project[50]

The IMP@CT project focuses on developing integrated modular plant and containerised tools for selective, low impact mining of small high-grade deposits. Following funding from the European Commission, the project has developed switch-on switch-off mining operations. This is supported by innovation in mining equipment and design to adapt to multiple deposits and minerals, while also allowing for whole operations to be moved relatively easily through standard logistical routes. The IMP@CT project demonstrated the technology on an antimony deposit in Gorazde, Bosnia, which is known for small but high grade deposits.[51]

Access to capital for mid-tier miners

With production of the major minerals in Australia dominated by Tier 1 mining companies, many of the critical minerals are expected to be developed by the junior to mid-tier mining companies (i.e. companies with a market capitalisation of <$5b). For example, whereas BHP is the only Tier 1 mining company extracting one or more of the shortlisted critical energy minerals, these minerals are the primary focus of 18 of the 50 largest mid-tier companies listed on the ASX.[52]

Given their comparatively small balance sheets, these mining companies are typically unable to fund capital intensive mining operations internally and therefore need to secure external capital (debt or equity). One of the primary enablers is the establishment of robust offtake agreements for the mined product. This challenge is exacerbated due to many of the shortlisted minerals (e.g. cobalt) existing in relatively volatile markets with a lack of pricing transparency. For instance, only 5 of the 15 critical minerals included in this report are currently listed on the London Metal Exchange (LME), with lithium soon to be added.[53]

46 Vella H (2019) Switch on switch off: rethinking how smaller deposits are mined. Mining Technology. Viewed 19 November 2020, <https://www.mining-technology.com/features/switch-on-switch-off-rethinking-how-smaller-deposits-are-mined/>.

47 Moskalyk R and Alfantazi A (2003) Processing of vanadium: A Review. Minerals Engineering. DOI: 10.1016/S0892-6875(03)00213-9.

48 Clout J (2013) Iron formation-hosted iron ores in the Hamersley Province of Western Australia. Applied Earth Science. DOI: 10.1179/174327506X138931.

49 Vella H (2019) Switch on switch off: rethinking how smaller deposits are mined. Mining Technology. Viewed 19 November 2020, <https://www.mining-technology.com/features/switch-on-switch-off-rethinking-how-smaller-deposits-are-mined/>.

50 IMP@CT (2020) Project. Viewed 19 November 2020, <http://blogs.exeter.ac.uk/impactmine/project/>.

51 Amaral de Oliveria V (2017) Integrated Mobile modularised Plant and Containerised Tools for selective, low impact mining of small high-grade deposits. <http://prometia.eu/wp-content/uploads/2014/02/04_Amaral_EXTRACTHIVE.pdf>.

52 ASX (2017) Metals & Mining Sector. Viewed 7 February 2021, <https://www.asx.com.au/documents/products/ASX-42800-Metals-and-Mining-Sector-Profile.pdf>.

53 LME (2020) Metals. Viewed 16 October 2020, <https://www.lme.com/en-GB/Metals>.

Further processing to high purity materials (discussed above) can also help overcome this challenge by enabling direct relationships and contracts between miners and OEMs. This can result in OEMs taking an equity stake in mining companies or providing an upfront payment for a longer term offtake which reduces the need for external financing. An innovative business model, more commonly known within the industry as 'streaming', has been particularly useful for providing up front capital and de-risking investment in secondary minerals.[54]

Sustainable products

The potential to supply sustainably mined products is a key comparative advantage for Australia. Sustainable production is broad and can include everything from waste, emissions, water and labour standards.[55] However, there is typically a higher cost of production in countries with governance structures in place to support sustainable products and this is often passed through as a premium to the customer.

The willingness of energy technology OEMs (and their suppliers) to pay that premium is uncertain. This is particularly the case at present given the more immediate need to be cost competitive with incumbent fossil fuel based technologies. Further, the dispersed global nature of many of these energy technology value chains makes it more challenging to certify sustainable products and the imposition of provenance frameworks in itself creates an additional layer of cost.

Access to capital is another considerable obstacle, with financial institutions enforcing tighter lending conditions relating to sustainability. While important, this makes it harder for mining companies to secure capital if unable to pass the added cost of compliance onto customers. Adding to this challenge is the emergence of border adjustment taxes that are assessed according to embodied emissions within export products. Such initiatives are currently being driven by the EU but will require alignment with the World Trade Organisation General Agreement on Tariffs and Trade as well as other relevant free trade agreements.[56]

A diverse range of technologies will be needed to minimise the cost of sustainable products. This is discussed below in 'integration of renewable energy technology', further in Section 1.1.3 (R&D) and in the specific value chain sections.

Integration of renewable energy

Integration of renewable energy into mining and processing operations will be critical to the minimisation of embodied emissions. Notably, Australia's prime renewable energy resources are often co-located with regional mining operations. Ongoing reductions in the capital cost of solar PV and wind has also meant that such forms of renewable energy generation are already providing economical energy solutions where there is an absence of grid connected transmission and a heavy reliance on diesel and natural gas.

Integration of renewable energy is particularly applicable to electricity intensive mining processes such as grinding mills, tailings filtration, water pumping, desalination, electrorefining and electrowinning.[57] For emerging Australian companies such as Element 25, feasibility studies involving integration of renewable energy has already been essential in demonstrating the economic viability of their Butcherbird manganese deposit (WA), despite having access to the Goldfields Gas Pipeline.

A series of established solutions also exist with respect to energy storage in order to help smooth the variability of renewable energy for continuous processes. This includes batteries as well as off-river pumped hydro. The latter is particularly applicable to mining operations as it involves development of two water reservoirs and leverages the difference in potential energy between them (e.g. Kidston mine).

The challenge is significantly greater for mining and processing operations dependent on high temperatures, with mature renewable and cost competitive solutions not as readily available. These are discussed further in Section 1.1.3.

1.1.2 Policy/regulatory

Supporting infrastructure

For a number of the shortlisted critical minerals, many of the prospective resources will require deployment of new infrastructure to improve their economic viability. Where required, supporting the deployment of adjacent (as opposed to mine specific) assets represents a lower risk investment for State and Federal governments.

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54 Refer to example of Wheaton Precious Metals; Streaming explained. Viewed 25 January <https://www.edisongroup.com/publication/streaming-explained/28132/>.

55 UNEP (2010) ABC of SCP: Clarifying Concepts on Sustainable Consumption and Production.

56 Hillman J (2013) Changing Climate for Carbon Taxes: Who's Afraid of the WTO?. The German Marshal Fund of the United States, US.

57 Diaz G et al. (2019) Carpe solem – solar mining opportunities for Chile: A paradigm changing perspective. DOI: 10.13140/RG.2.2.28200.11525.

This approach, which has been successfully pursued by public financing organisations such as the Northern Australia Infrastructure Facility (NAIF), is particularly important in simultaneously improving the economics of a given mining operation and providing public benefit in the region. Export Finance Australia is another public financing institution focused on infrastructure development as it relates to various export opportunities including mining and critical minerals specifically.[58]

Case Study: Northern Australia Infrastructure Facility[59]

NAIF is a Commonwealth Government finance provider of projects focused on unlocking economic and employment opportunities for Northern Australia. In this role, NAIF is investing $5 billion across a range of projects including mining and manufacturing. The agency uses innovative financing models and longer term finance (up to 30 years) to incentivise private sector investment in publicly owned assets and finance mine infrastructure that supports public benefit in the region. This includes conditional approval for Verdant Minerals to build accommodation, rail and water pipelines for the Ammaroo Phosphate project which is expected to deliver $160 million of public benefit to the region.[60]

Notably, to address the need for cost competitive low emissions energy, there is a unique opportunity for infrastructure agencies to work with Australia's renewable energy organisations such as Australian Renewable Energy Agency (ARENA) and the Clean Energy Finance Corporation (CEFC) to help integrate both emerging and mature renewable energy generation assets.

Royalties system incentives

Royalty systems are used across Australian states and territories to incentivise downstream processing within mining operations.[61] Under these programs, the royalty amount payable is reduced based on the added value of the product (i.e. from ore to metal), otherwise known as *ad valorem*.[61] However, the current regime does not extend to the production of alloys and chemicals (e.g. battery precursors).[62] Given there will be an ongoing requirement for these products as part of the energy transition, revision of royalty programs and clear definitions around the 'mine gate' could be considered to stimulate investment in these downstream activities.

Improved RD&D ecosystem

As previously mentioned, the emergence of critical energy minerals will require ongoing development of bespoke mining and processing technologies to operate smaller mines, exploit secondary minerals, produce cost competitive higher grade materials and reduce environmental footprint. This is likely to require an improved RD&D ecosystem to enable the industry (including the 'Mining, Equipment, Technology and Services' (METS) sector) to efficiently draw on the breadth and depth of capabilities within the Australian research community and avoid duplication of efforts. WA is one state that has improved the efficiency of industry/research collaboration through the Minerals Research Institute (MRIWA) which is a model that could be replicated or centralised across the country.

Case Study: Minerals Research Institute of Western Australia[63]

The MRIWA supports applied minerals research by enabling collaborations between industry, government and the research community. The Institute focuses their research priorities on finding more viable resources, expanding economic and safe extraction, processing to add value, infrastructure, logistics and new products and markets. For example, MRIWA has invested in the Future Battery Industries Cooperative Research Centre (FBICRC) to encourage collaboration across industry and academia to improve recovery of metal lost in conventional processing of nickel and cobalt.[64]

58 Export Finance Australia (2020) Project & Structured Finance. Viewed 20 November 2020, <https://www.exportfinance.gov.au/what-we-do/project-structured-finance/>.

59 NAIF (2020) Investing for impact across the north. Viewed 16 October 2020, <https://naif.gov.au/>.

60 NAIF (2020) NAIF Investment Decisions and Conditional Approvals as at July 2020, <https://naif.gov.au/wp-content/uploads/2016/08/NAIF-Investment-Decisions-and-Conditional-Approvals-as-at-July-2020-FINAL.pdf>; ICN (2020) Ammaroo Phosphate Project. Viewed 23 December 2020, <https://gateway.icn.org.au/project/3993/ammaroo-phosphate-project>.

61 Gui P (2012) Mineral royalties and other mining specific taxes. International Mining for Development Centre. International Mining for Development Centre, Australia.

62 CME (2020) 2020–21 Budget Submission.

63 MRIWA (2020) Research Priority Plan.

64 MRIWA (2020) Hydrometallurgical processing for nickel and cobalt ores, concentrates, tailings, wastes – Stage 1. Viewed 23 December 2020, <https://www.mriwa.wa.gov.au/research-projects/project-portfolio/hydrometallurgical-processing-for-nickel-and-cobalt-ores-concentrates-tailings-wastes-stage-1/>.

Skills and knowledge development

The changing nature of Australia's mining sector will require investment in education and 'upskilling' the existing workforce. Despite having an established workforce supporting conventional extraction and beneficiation processes (i.e. commodity minerals), there is an absence of capabilities relating to production of high purity materials, chemicals and specific compounds (e.g. battery precursors).[65]

Although government continues to play a key role in funding and regulating education, private sector entities make up a greater share of tertiary providers.[66] Government may therefore need to collaborate with industry and research to create a skills development strategy and to align formal and non-traditional (i.e. 'on-the-job') program delivery.[67]

1.1.3 RD&D

Ore characterisation

Improved ore characterisation plays an important role in reducing exploration costs and in optimising process flows to enhance plant throughput and efficiency.[68] This includes a more comprehensive understanding of ore formation to inform discovery of high quality deposits and exploration strategies which is particularly important for secondary minerals.[69] Improved ore characterisation is also crucial to exploration of minerals facing declining ore grades (e.g. copper) and more complex metallurgy (e.g. REEs),[68] and provides assistance to junior miners who may not have the resources or expertise to undertake costly widespread exploration.[70]

Emerging spectroscopic techniques such as near-infrared spectroscopy allows for infield testing and real time data during drilling and exploration.[71] Further, whereas current technologies are typically calibrated to be mineral specific, these spectroscopic techniques can allow for multi-mineral characterisation (in the same ore) which can help economic recovery of secondary minerals. They also provide both qualitative and quantitative data which is integral for low concentration critical minerals in newly uncovered deposits.[72]

Centralised repositories of mineral data that leverage improved ore characterisation will also be crucial for the mining sector. For instance, development of Australia's National Virtual Core Library has enabled researchers, geological surveyors and the mining industry to access drill core libraries from state and territory governments in one location.[73] Another example is the Australian Critical Minerals Portal that aims to provide users with a central source of geological information and data to assist critical mineral discovery, as well as tools for decision-making on exploration, mine development and investment.[74]

Ore sorting

Ore sorting is the process of separating raw feed based on ore quality and mineral composition to improve recovery rates and obtain higher concentration inputs for further processing. This results in reduced electricity and water use to extract the desired material and minimises waste (tailings) generated from processing activities.[75] Magnetic separation has traditionally been used as the primary form of sorting.[76]

Recently however, mine sites have shifted to 'sensor-based' ore sorting which makes use of modified analytical techniques to achieve more accurate and timely characterisation of minerals in a given feed. These techniques include x-ray transmission, near-infrared spectroscopy and magnetic resonance. The applicability of each is dependent on the target mineral.[77]

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65 Best A and Vernon C (2020) State of Play: Australia's Battery Industries as at March 2020. CSIRO, Australia; Hayes P C (2019) The World Needs Metallurgical Process Engineers. Journal of the Minerals, Metals & Materials Society. DOI: 10.1007/s11837-018-03316-4.

66 OECD (2020) Spending on tertiary education (indicator). DOI: 10.1787/a3523185-en.

67 For example, co-created programmes, open online programmes, or work trial programmes; CSIRO (2020) The Value of Science and Technology. CSIRO, Australia.

68 Baum W (2014) Ore characterization, process mineralogy and lab automation: A roadmap for future mining. Minerals Engineering. DOI: 10.1016/j.mineng.2013.11.008.

69 Vigneresse J (2019) Addressing ore formation and exploration. Geoscience Frontiers. DOI: 10.1016/j.gsf.2018.09.017.

70 Gemmel B (2011) CRC bid provides opportunities for SMEs. Ore Solutions: Newsletter of Codes.

71 van der Meer F (2018) Near-infrared laboratory spectroscopy of mineral chemistry: A review. International Journal of Applied Earth Observation and Geoinformation. DOI: 10.1016/j.jag.2017.10.004.

72 Haldar SK (2013) Mineral Processing. SK Halder (ed.) Mineral Exploration: Principles and Applications. Elsevier, US.

73 AuScope (2020) National Virtual Core Library: Building a Mineralogy database of Australia. Viewed 7 January 2021, <https://www.auscope.org.au/nvcl/>.

74 Critical Minerals Facilitation Office – Australian Critical Minerals Portal, viewed 1 February 2021 <https://portal.ga.gov.au/persona/cmfo>.

75 NextOre (2020) Bulk ore sorting: Whitepaper.

76 Haldar SK (2013) Mineral Processing. Mineral Exploration. Elsevier, US.

77 Robben C and Wotruba H (2019) Sensor-based ore sorting technology in mining – past, present and future. Minerals. DOI: 10.3390/min9090523.

Increased confidence and adoption of these technologies is expected as high capacity, multi-mineral sorting installations are trialled across mine sites.[77] Efforts to decrease costs by increasing capacity, flexibility and detection efficiency of the equipment are ongoing. Development of integrated sensor-based ore sorting and comminution circuits (e.g. crushing, grinding) are another current priority. This is the focus of emerging companies such as Next Ore who are implementing magnetic resonance sensors to improve lithium recovery and reduce waste.

Case Study: Next Ore[78]

NextOre's bulk ore sorting systems use magnetic resonance sensors to provide real-time measurements of feed materials to determine metal content and ore grade estimates, allowing the separation of high value material from waste. The system can also be used to separate ore types for different process routes. Benefits of the technology include reduced operational costs, water and energy consumption, decreased tailings production, and increased recovery of minerals that may have otherwise been rejected. The bulk ore sorting system can be fitted over existing industry conveyor belts, improving integration into an existing or new mine site. This technology is suitable for minerals including copper, nickel, bismuth and sulphide.

In-situ mining

In-situ mining, or in-situ recovery (ISR), is a hydrometallurgical process that involves the extraction of minerals using a leaching solution. The desired minerals are extracted from the leach solution which is subsequently reconditioned for reuse. Although the recovery rates are lower than conventional mining and processing, this sidesteps the need to mine ore and bring it to the surface for conventional processing. This minimises environmental impact and has the potential to make extraction from some deposits more economically viable. Environmentally friendly leaching solutions such as citric acid are also currently being pursued.[79] Further, ISR is more favourable for renewable energy integration given that it primarily involves pumping solution through a particular deposit.

ISR is already in commercial use for a number of minerals. It is used in more than 50% of uranium production and has been implemented at industrial scale for copper, gold, silver, lithium and zinc.[80] It has also been used at pilot scale for a variety of rare earth elements and other critical energy minerals such as nickel, cobalt, vanadium, manganese and PGEs.[81] REE and lateritic deposits of nickel and cobalt currently present as strong prospects for ISR.[81]

While each metal has its own risks with regard to ISR, overarching challenges typically include the requirement for more complex resource estimation and assessments compared to conventional mining. Ore morphology, mineralogy, hydrogeology, groundwater chemistry, and microbial conditions of the mining zone all need to be understood to establish an appropriate leaching system.[82] Further, ISR is not applicable in every situation given that its viability depends on factors such as water permeability, whether minerals can be readily dissolved and recovered from a leaching solution and the ability to control the process to ensure minimal environmental damage.[83]

Other barriers include slow uptake due to lack of expertise and experience, poor recovery rates for some sites due to permeability of rock formations and environmental considerations associated with the dispersal of leaching solution beyond the mine site.[84] Again, this can be improved by further ore body characterisation, improved containment monitoring, more selective and benign leaching solutions, and tools to enable better access to orebodies.[85]

Tailings reprocessing

As mentioned, critical energy minerals that exist as by-products of major minerals and deemed sub-economic typically end up in mine tailings. For example, the Olympic Dam deposit is one of the largest REE resources in Australia, yet optimisation of the primary minerals including copper, uranium, gold and silver, has meant that it is more economical to send REE to tailings than process them.[86]

78 NextOre (2020) Bulk ore sorting: Whitepaper.

79 Haschke M et al. (2016) In-Situ Recovery of Critical Technology Elements. Procedia Engineering. DOI: 10.1016/j.proeng.2016.02.082.

80 Seredkin M et al. (2016) In situ recovery, an alternative to conventional methods of mining: Exploration, resource estimation, environmental issues, project evaluation and economics. Ore Geology Reviews. DOI: 10.1016/j.oregeorev.2016.06.016.

81 Seredkin M (2019) In-situ recovery for non-uranium metals. ALTA 2019 In Situ Recovery Proceedings, Perth, Australia.

82 Seredkin M et al. (2016) In situ recovery, an alternative to conventional methods of mining: Exploration, resource estimation, environmental issues, project evaluation and economics. Ore Geology reviews. DOI: 10.1016/j.oregeorev.2016.06.016.

83 Government of South Australia (n.d.) In situ recovery (ISR) mining. Viewed 13 October 2020, <https://www.energymining.sa.gov.au/minerals/mining/mines_and_quarries/in_situ_recovery_ISR_mining>.

84 Seredkin M (2019) In-situ recovery for non-uranium metals. ALTA 2019 In Situ Recovery Proceedings, Perth, Australia; De Silva V et al. (2019) An artificial fracture simulation technique for enhanced in situ recovery using non-explosive demolition agents. ALTA 2019 In Situ Recovery Proceedings.

85 Mining3 (2018) In-situ recovery – a move towards 'keyhole mining'. Viewed 7 January 2021, <https://www.mining3.com/situ-recovery-move-towards-keyhole-mining/>.

86 Australia G (2013) Australia's Mineral Resource Assessment 2013. <BHP (2020) Olympic Dam. Viewed 7 January 2021, <https://www.bhp.com/our-businesses/minerals-australia/olympic-dam/>.

Commercially viable extraction of high value critical energy minerals (e.g. PGEs) from tailings remains an area of significant interest.[87] This is particularly the case as ore grades continue to degrade globally and the price of critical minerals increases. For instance, tailings in the Bushveld Complex of South Africa are now being processed to recover chromium, as well as PGEs.[88] However, this is unlikely to reduce overall tailings volumes and reprocessing techniques may introduce additional contaminants to the waste that are difficult to manage.

While there are a number hydro- and pyro-metallurgical methods that can be used to extract additional minerals from tailings, leaching is the most prominent technology under investigation for efficient mineral extraction. Flotation technologies are also expected to play an important role in reprocessing tailings for recovery of minerals such as cobalt and copper.[89]

Bioleaching

Bioleaching[90] is an emerging technique that relies on microorganisms (rather than chemical leaching) to extract or recover metals into a solution. This can be applied to ores, concentrates, tailings or waste (e.g. tailings, slags, pyritic ashes or e-waste). It is applicable to a wide range of minerals, though most developed for sulphide ores (i.e. extraction of copper, gold, nickel and cobalt).[91] Bioleaching can be implemented in reactors, vats or *in situ* in ore bodies. Benefits include low energy consumption, emissions and toxicity as well as economically viable extraction from low-grade and complex ores or wastes.[92] While roughly 10–15% of global copper and 5% of global gold production are dependent on biohydrometallurgy,[93] further research on bioprospecting, engineering and optimising bioleaching microorganisms and processes is expected to unlock more complex ores and waste streams.[94]

Integration of renewable energy for high temperature heat

As mentioned, while integration of renewable energy for electricity intensive processes has been found to be cost competitive, the challenge is greater for processes requiring high temperature heat. Heat is used across multiple stages in mining and metal production operations, but most intensely during ore processing and refining. Low temperature processes (<250°C) can consume 10–20% of the total energy required to attain the product. Other processes such as roasting can require temperatures between 500 to 700°C. [95]

Two types of technologies exist to support incorporation of renewable heat solutions for mining and processing operations, namely CSP (discussed further in Section 4.2.2) and alternative fuels derived from hydrogen or biomass. Hydrogen should also be recognised as an alternative method of longer-term (i.e. weekly to monthly) energy storage.

Alternative fuels

Hydrogen has broad applications across mining and processing including transport for heavy haulage, energy storage and as a feedstock for a number of electrochemical processes. Notably, it can replace natural gas and coal to produce high temperature heat for mineral processes such as calcination. There are minimal technical barriers associated with the use of hydrogen for combustion with the primary challenges relating to development of the requisite safety standards and lowering the current cost of hydrogen production.

Similarly, there are minor technical barriers to the combustion of biomass to produce high temperature heat. Rather, challenges relate to the proximity of available biomass resources at adequate volumes. Common biomass sources in Australia are seasonal and not conveniently located for transport to mineral refineries.

87 Falagan C et al. (2017) New approaches for extracting and recovering metals from mine tailings. Minerals Engineering. DOI: 10.1016/j.mineng.2016.10.008.

88 Deloitte (2019) Converting tailings dumps into mineral resources. Viewed 13 October 2020, <https://www2.deloitte.com/za/en/pages/energy-and-resources/articles/converting-tailings-dumps-into-mineral-resources.html>.

89 Lutandula M and Maloba B (2013) Recovery of cobalt and copper through reprocessing of tailings from flotation of oxidised ores. Journal of Environmental Chemical Engineering. DOI: 10.1016/j.jece.2013.08.025.

90 Also called microbial leaching.

91 Kaksonen AH et al. (2018) Recent progress in biohydrometallurgy and microbial characterization. Hydrometallurgy. DOI: 10.1016/j.hydromet.2018.06.018; Srichandan H et al. (2019) Bioleaching approach for extraction of metal values from secondary solid wastes: A critical review. Hydrometallurgy. DOI: 10.1016/j.hydromet.2019.105122; Dresher WH (2004) Producing Copper Nature's Way: Bioleaching. Viewed 27 January 2021 <https://www.copper.org/publications/newsletters/innovations/2004/05/producing_copper_natures_way_bioleaching.html#:~:text=Bioleaching%20involves%20the%20use%20of,by%20the%20sulfuric%20acid%20formed>; Watling HR (2006) The bioleaching of sulphide minerals with emphasis on copper sulphides – A review. Hydrometallurgy. DOI: 10.1016/j.hydromet.2006.05.001; Angloamerican (2021) Bioleaching Definition & Process. Viewed 22 January 2021, <https://www.angloamerican.com/futuresmart/stories/our-industry/mining-explained/mining-terms-explained-a-to-z/bioleaching-definition-and-process>.

92 Srichandan et al. (2019) Bioleaching approach for extraction of metal values from secondary solid wastes: A critical review. Hydrometallurgy. DOI: 10.1016/j.hydromet.2019.105122.

93 Biohydrometallurgy is the broader field concerned with the interactions between microbes and minerals, which includes bioleaching.

94 Kaksonen AH et al. (2018) Recent progress in biohydrometallurgy and microbial characterization. Hydrometallurgy. DOI: 10.1016/j.hydromet.2018.06.018.

95 ITP Thermal (2019) Renewable energy options for industrial process heat. ARENA, Australia.

Provenance tracking

Mineral provenance tracking is gaining increasing importance due to concerns over product quality, sustainability and legality across the supply chain. Blockchain is one technological solution already emerging in some mineral supply chains. For instance, this technology has been employed by companies such as Everledger to ensure provenance in the diamond industry.[96]

With respect to critical energy minerals, companies such as Cobalt Blockchain have developed a software based platform to ensure ethical provenance of cobalt extracted in the DRC.[97] However, primary barriers to ongoing development relate primarily to the quality of information in mineral extraction and processing (i.e. ensuring products are appropriately identified and accounted for in complex supply chain processes).[98]

One potential enabler is geochemical fingerprinting. This technology makes use of laser-induced breakdown spectroscopy to generate an emission spectrum for a given ore sample. This spectrum, or 'geochemical fingerprint', is indicative of the unique distribution of minerals found in a specific geographic location; and could be compared with mineral samples received by the customer to determine provenance validity. In order for geochemical fingerprinting to become effective in practice, a database of ore samples of known origin from around the world need to be made available.[99] The technology remains at an early stage, with some speculation over its potential effectiveness given the difficulty in accurately generating a comparable spectra of a metal after it has been extracted from the ore.

1.2 Manufacturing

1.2.1 Commercial

Partnerships

For key energy technologies, considerable investment in the US, EU and Asia over the preceding decades has led to the development of significant know-how and intellectual property (IP) relating to both manufacturing processes and technology design. As a consequence, despite typically having the requisite minerals or materials, Australia will often run into IP barriers relating to manufacture of components, particularly where they carry a high degree of specification to ensure optimal performance. Local manufacturing will therefore often depend on licencing of IP and partnering with international OEMs.

One of the primary obstacles to attracting these OEMs onshore is that they often establish manufacturing precincts adjacent to R&D collaborators in order to promote ongoing improvement in technology design and performance. For example, the Central Taiwan Science Park has attracted a cluster of OEMs and research institutes focused on continued improvement as well as high volume manufacture of semiconductors and silicon wafers for solar PV.[100]

Building on the need for a more coordinated research ecosystem discussed in Section 1.1.2, a similar theme occurs in relation to manufacture of energy technologies. As demonstrated throughout the value chain analysis, Australia has deep R&D capabilities across each of the shortlisted technologies. Coordination of these activities can provide a foundation for precinct development and stronger partnerships with local and international OEMs. ACE-EV, a prospective Australian EV OEM with aspirations to set up onshore manufacturing operations is one example of an emerging company drawing on a broad range of Australian IP to develop their vehicles.

96 EverLedger (2021) Industry solutions: diamonds. Viewed 15 January 2021, <https://www.everledger.io/industry-solutions/diamonds/>.

97 Newswire (2020) Cobalt Blockchain announcement regarding private placements. Viewed 13 October 2020, <https://www.newswire.ca/news-releases/cobalt-blockchain-announcement-regarding-private-placements-838823928.html>.

98 RCS Global (2017) Blockchain for traceability in minerals and metals supply chains.

99 Arnaud C.H (2012) Fingerprinting conflict minerals. Chemical & Engineering News. Viewed 15 January 2021, <https://cen.acs.org/articles/90/i18/Fingerprinting-Conflict-Minerals.html>.

100 Fulco M (2019) What are Taiwan's Science Parks? Taiwan Business Topics. Viewed 7 January 2021, <https://topics.amcham.com.tw/2019/03/what-are-taiwans-science-parks/>.

Case Study: ACE EV[101]

ACE EV is an energy systems manufacturer and software company with aspirations to deploy their core technology through the roll out of EVs. The system employs a meter and charge technology, which allows for monitoring of system use to ensure optimal battery performance. The company is developing their technology around LFP batteries which are suitable for Australian temperatures, are low-cost and have a range sufficient for urban distances.

ACE EV is collaborating with the University of Southern Queensland on bio-engineering and nanotechnology, the University of New South Wales on incorporation of a solar PV skin onto vehicles, and Flinders University on design simulation technologies for testing and compliance as well as modular manufacturing. The company is also collaborating with end-of-life battery initiatives to design a cradle-to-grave solutions.

ACE EV's first vehicle was built in 2019 in Brisbane and the company has designed their factory to produce 24,000 vehicles per year with plans to scale up to 50,000 by 2025 based on the current interest received.

The other primary barrier to international OEMs investing in Australia is the need for proximity to customers to reduce supply chain costs and improve security of supply. However, despite often being recognised as a smaller market, it is important not to underestimate the scale of energy technology expected to be deployed in Australia and its role in de-risking investment in domestic manufacture for both local and export markets.

Domestic demand

By 2050 and with some of the strongest renewable energy resources globally, Australia could deploy 100 GW of solar PV, 53 GW of wind and 212 GWh of stationary battery storage for commercial and residential applications. Importantly however, it is Australia's opportunity to become an exporter of renewable energy (via hydrogen or long distance high-voltage direct current cables) that could see an additional step change increase in local deployment of renewable energy.

For instance, initiatives such as the Asian Renewable Development Hub situated in the Pilbara region of WA is expected to involve the deployment of over 26 GW of wind and solar generation, and up to 23 GW of hydrogen production infrastructure.[102] Further, once a final investment decision is reached, the hub has a 10 year development timeline that could complement the construction of domestic solar, wind and electrolyser manufacturing facilities.[102]

Given the proximity of a significant minerals endowment and strong renewable energy resources in North West Australia, there is also an opportunity to develop centralised manufacturing and recycling facilities that are powered by renewable energy. This can again increase the deployment of renewable energy systems and also place further downward pressure on the price of electricity.

1.2.2 Policy/regulatory

Local content quotas

The imposition of local content quotas alongside energy technology deployment are likely to be important in de-risking investment in domestic manufacturing value chains. These quotas could exist in two parts.[103] The first part would involve the imposition of quotas on technologies/components manufactured in Australia. Subsequent local content quotas on the underlying materials could then be implemented. Note however that imposing these quotas may run contrary to various free trade agreements and these should be appropriately considered as part of any policy roll out. Further, a series of other subsidies may be needed to mitigate the impact on levelised cost of energy (LCOE), particularly during industry scale up.

A strong precedent for the imposition of local content quotas in the energy transition may be found in the Victorian Renewable Energy Targets (VRET).

Case Study: Victorian Renewable Energy Targets[104]

The VRET has set a target of 50% renewable energy within the state by 2030. Alongside this, the Victorian Government has issued the Victorian Renewable Energy Auction Scheme to place 64% local content target on VRET projects. This includes businesses across Australia and New Zealand. Alongside local content, the Scheme places a 90% target on local operations and 90% on local steel. The VRET auction has successfully contracted 6 new renewable energy generation projects with local content requirements, including 673.5 MW of wind and 254.5 MW of solar PV.

101 AU manufacturing (2020) ACE-EV gets electric vehicle supercharge in federal budget. Viewed 11 January 2021, <https://www.aumanufacturing.com.au/ace-ev-gets-electric-vehicle-supercharge-in-federal-budget>.

102 AREH (2020) About the Asian Renewable Energy Hub. Viewed 25 January 2021, <https://asianrehub.com/about/>.

103 DELWP (2019) Victorian Renewable Energy Target: 2018–2019 Progress Report. Department of Environment, Land, Water and Planning, Australia.

104 DELWP (2018) VRET auction benefits. Department of Environment, Land, Water and Planning, Australia; DELWP (2018) VRET 2017 Reverse Auction Outcomes Question and Answers. Department of Environment, Land, Water and Planning, Australia.

Returns on public sector investment

Australia has a robust public sector investment framework in place to support the development of the renewable energy sector. ARENA is a grant organisation designed to increase the supply of renewable energy by supporting earlier stage RD&D. The CEFC has a similar remit but exists as a 'development bank' that requires a return on investment.

Importantly however, there is nothing in this framework that ties early stage RD&D investment to local manufacturing. Such a mechanism could ensure a further return on investment of public funds and consolidation of value chains onshore, thereby minimising commercialisation of Australian IP overseas and promoting competitive manufacturing precincts. An example of the effectiveness of these linkages may be found with the United Kingdom's Advanced Propulsion Centre (APC).

Case Study: Advanced Propulsion Centre[105]

The APC is a collaboration between the UK government and automotive industry to fund RD&D with the primary intention of promoting local vehicle manufacture. The APC has undertaken 51 projects and has over 178 member organisations including major OEMs. One such project is the commercialisation of Alistek's NOXTEK technology to filter nitrogen oxides from cabin air and exhaust emissions.[106] APC funding and automotive industry networks allowed Alistek to efficiently identify manufacturing partners which then supported onshore commercialisation.

1.3 Recycling

The scale of technology deployment expected to underpin the global energy transition will lead to substantial waste flows at the end of asset life. Pro-active and co-ordinated action from industry, government and the research sector is therefore needed to ensure a high degree of resource circularity can be achieved, particularly in relation to critical energy minerals due to associated supply risks. If successful, this can enable the following benefits:

1. reduced environmental impact by minimising toxic waste flows and lowering volumes of virgin materials required (i.e. to reduce overall mining footprint)
2. increased flexibility in material flows which will be important in emerging markets with supply and demand volatility
3. reduced loss (and increased re-use) of high value minerals and the realisation of new economic opportunities associated with the recycling industry.

1.3.1 Commercial

Creating a circular economy for energy technologies will require OEMs and recycling proponents to rethink business models and system design. Some of the measures required are detailed below.

Product design

At present, energy technologies are designed to optimise asset life and performance. However, given the mineral intensity and supply risk of critical minerals, designing products for secondary use and recycling is likely to become increasingly important over the coming decades. For instance, this may involve reducing the number of impurities introduced to minerals at varying stages of the value chain to ensure efficient recovery of high purity material. It may also include designing technologies that are easier to dismantle at the end of asset life or easily transitioned to secondary applications once their operating performance drops below a certain threshold.

Finance leases

Finance leases provide a more affordable point of entry for energy technologies that typically have high capital costs. OEMs also benefit from this arrangement by retaining additional control over the asset. This benefit is furthered in the context of resource circularity, as OEMs can establish offtakes with recycling proponents where the quantity, materials and timing of asset return are known. This is critical for efficient and cost-effective recycling as it allows asset operators to better understand inflows and tailor refining processes, particularly where the product has a high volume of trace contaminants.

105 APC (2020) The Power of Collaboration. Viewed 7 January 2021, <https://www.apcuk.co.uk/the-power-of-collaboration/>.

106 APC (2020) Making the leap: How APC support enabled one SME to break into the automotive industry. Viewed 7 January 2021, <https://www.apcuk.co.uk/case_study/making-the-leap-how-apc-support-enabled-one-sme-to-break-into-the-automotive-industry/>.

107 Dominish E et al. (2017) Australian Opportunities in a circular economy for metals: Findings of the Wealth from Waste Cluster. Wealth from Waste, Australia.

Asset centralisation

For many of the energy technologies, although the underlying materials can technically be recycled, economic barriers often relate to the high cost of collection and the need for economies of scale to offset high capitals costs.[107] Specifically in relation to the latter, there is a significant opportunity to achieve those economies of scale by centralising primary minerals processing and recycling. This may be enabled by the use of metallurgical processes that can process both virgin and recycled materials. Asset centralisation is also important in terms of allowing recycling proponents to more easily secure offtakes for the recovered minerals and in promoting reverse logistics where possible.

The cost of transport, which is often higher due to poor packing density of assembled technologies, can be alleviated via the introduction of a 'hub and spoke' model. This involves disassembling the technology at distributed locations before transporting relevant components to a centralised processing facility. Such a model can mitigate challenges relating to transport safety and is particularly relevant in the context of dispersed, high volume technologies such as batteries and fuel cells. Based in Canada, Li-Cycle is one company leading the development of hub and spoke recycling.

Case Study: Li-cycle (Canada)[108]

Li-cycle is a closed loop, advanced LiB recycling initiative which has achieved recovery rates of greater than 95% of all materials. Li-cycle's business model involves decentralised shredding and crushing (i.e. 'Spoke'), which is deployable in locations across the world, and a centralised 'Hub' for hydrometallurgical processing. The company has rolled out its first two commercial 'spokes' and plans to build its commercial 'Hub' in 2021 in New York State, USA (the largest LiB recycling plant in North America).

1.3.2 Policy/regulatory

Nationally consistent waste regulations

Several jurisdictions around Australia have banned disposal of e-waste in landfill (including batteries and solar PV). To date however, differences in state regulations and policies have led to adverse, inconsistent and inefficient outcomes, such as illegal dumping and diversion of waste to other states.[109]

A national waste and landfill policy for energy technologies could therefore be implemented to better manage relevant waste streams. This could include uniform fees and charges, as well as targets and incentive based approaches which are all crucial to minimising the volumes of waste sent to landfill.[109] Other enablers include standardised labelling, classification of products and collections planning to prevent co-mingling of waste streams that are unsuitable for specific processing technologies.

Product stewardship

Product stewardship will be essential to achieving high recovery rates, particularly where recycling projects are not economically viable. Of the shortlisted energy technologies, only batteries and solar PV are currently included in the Federal Product Stewardship Act 2011.

Best practice product stewardship schemes should not be limited to technology OEMs but include all suppliers of raw materials and product recyclers. Given the chemical intensity of minerals processing, guidelines on chemicals management should also be considered. Further, resource efficiency and reducing the environmental impact of goods and services at exploration and mining stages should be included given that it is part of the full product lifecycle.[110]

Extender Producer Responsibility schemes, where producers are responsible for financing and/or physical disposal of products at end-of-life (currently applied to tyres) should also be considered in order to help finance recycling facilities. Such a program is currently being explored for wind turbines in France and Germany due to their size and consequent strain placed on landfill.[111]

108 Li-cycle (2021). Technology. Viewed 15 January 2021, <li-cycle.com/technology>; Li-cycle (2021). About. Viewed 15 January 2021, <li-cycle.com/about>.

109 Environment and Communications References Committee (2018) Never waste a crisis: the waste and recycling industry in Australia. Commonwealth of Australia, 2018; Laviano H et al. (2017) An Inquiry into the Waste and Recycling Industry in Australia: A submission to the Environment and Communications References Committee. Submission to the Senate Inquiry. Submission 63.

110 DIIS (2011) Leading Practice Handbooks for Sustainable Mining. Viewed 18 January 2021, <https://www.industry.gov.au/data-and-publications/leading-practice-handbooks-for-sustainable-mining>; ICMM (2006) Product Stewardship. Viewed 18 January 2021, <https://www.icmm.com/en-gb/metals-and-minerals/managing-metals-sustainably/product-stewardship>; ICMM (2021) Chemicals Management. Viewed 18 January 2021, <https://www.icmm.com/en-gb/metals-and-minerals/managing-metals-sustainably/chemicals-management; SAICM, UNEP (2020) SAICM Overview. Viewed 18 January 2021, <https://www.saicm.org/About/SAICMOverview/tabid/5522/language/en-GB/Default.aspx>.

111 Wind Europe (2020) Accelerating Wind Turbine Blade Circularity. CEFIC.

Global recycling hub

It is unlikely that the volumes of energy technologies deployed in Australia will enable recycling assets to be economically viable given the high capital cost of processing facilities. With this, there may be a long term opportunity for Australia to establish itself as a recycling hub for the Asia-Pacific region.

To facilitate this, international engagement will be required to build consistent industry standards that provide sufficient details regarding technology materials and compositions without infringing on IP. Further, engagement with international governments and OEMs will be important in facilitating sharing of information relating to processing technology, waste flows, and markets for recycled materials. This can inform local policy and encourage cross-border collaborations. Further, engagement with regulatory bodies regarding the treatment and shipping of 'hazardous goods' (e.g. batteries) will be required to facilitate trading of waste products.

1.3.3 RD&D

Metallurgical processing technologies

Although recycling technologies are generally well established for high volume conventional steels and alloys used in the wind and CSP industry, significant RD&D is required to address the emerging flows of complex waste streams from the other shortlisted energy technologies. This includes mixed metals in fuel cells, batteries, solar PV and permanent magnets as well as large flows of composite materials from wind turbine blades.

Various electrochemical and metallurgical processes can be applied to complex mixed metal wastes for separation. However, these are often cost prohibitive and energy intensive due to the high processing temperatures required. They are also typically multi-stage processes that can generate substantial toxic waste. Further R&D is therefore required to improve these processes.

Recent developments include 'cyclone' electrowinning to produce high purity products without the need for costly solvent extraction.[112] This and other electrowinning techniques are applicable to a broad range of metals (e.g. aluminium, copper), and the solvent may be varied to achieve the desired outcome (e.g. recovery, purification, selective deposition).[113]

Stocks and flows modelling

Stocks and flows modelling is key to obtaining a whole of system view of materials use in different technologies. This can inform strategic decision-making to achieve optimised outcomes relating to the recovery and use of critical energy minerals. For instance, early identification of bottlenecks in critical minerals supply and surges in the influx of materials from end-of-life assets can help planning of raw material extraction and scale up of recycling assets.

112 Memom AH et al. (2017) Design for recovery of precious and base metals from e-waste using electrowinning process. International Journal of Advanced Research in Engineering, Science & Technology 4(5), 579–587.

113 Neto IF et al. (2016) A simple and nearly-closed cycle process for recycling copper with high purity from end life printed circuit boards. Separation and Purification Technology. DOI: 10.1016/j.seppur.2016.03.007.

2 Solar PV

2.1 Value chain opportunities

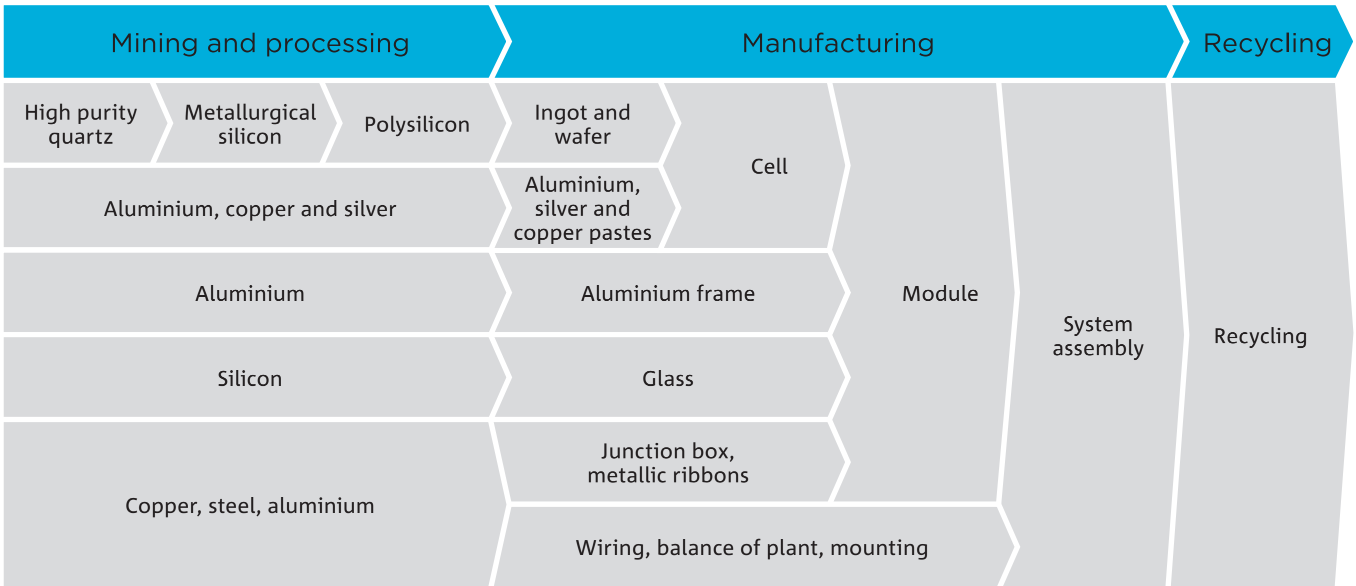

Figure 13: The crystalline silicon PV value chain

2.1.1 Critical minerals mining and processing

As discussed in Section 2.2 Part I (and further in Appendix B), should domestic HPQ resources be developed, the opaque and highly concentrated nature of the global industry means there is a significant opportunity for Australia to develop the upstream portion of the solar PV value chain.

HPQ refining takes place through a series of physical, chemical and thermal processes (i.e. crushing, sorting, flotation, acid leaching, hot chlorination and heat treatment). Various production grades exist which are certified under the IOTA standard established by Unimin Corp/Sibelco and the Quartz Corp.

Metallurgical silicon is then produced by reducing (i.e. removing the oxygen from) silicon dioxide in an arc furnace using a source of carbon (i.e. a carbothermal reaction).[114] This process is relatively straightforward but energy intensive, requiring temperatures of ~2000°C.[115] Whereas other countries may be required to rely on the use of coal which introduces other trace contaminants, a comparative advantage for Australia is the availability of biomass derived charcoal as a reductant, as per the case of Simcoa (based in WA).[116]

114 Chigondo F (2018) From Metallurgical-Grade to Solar-Grade Silicon: An Overview. Silicon. DOI: 10.1007/s12633-016-9532-7; Woodhouse M et al. (2018) Crystalline Silicon Photovoltaic Module Manufacturing Costs and Sustainable Pricing: 1H 2018 Benchmark and cost Reduction Road Map. NREL, US.

115 Barbouche M et al. (2015) Electric arc furnace design and construction for metallurgical and semiconductor research. International Journal of Advanced Manufacturing Technology. DOI: 10.1007/s00170-015-7424-4.

116 Haque N (2015) Biomass to charcoal – prospects for Australian forest industries. Forest & Wood Products Australia. <https://www.fwpa.com.au/rd-and-e/r-and-dworks-webinars/875-biomass-to-charcoal-prospects-for-australian-forest-industries.html>.

Case Study: Simcoa

Simcoa, a subsidiary of Shin-Etsu Chemical Co Ltd, is Australia's only domestic manufacturer of metallurgical-grade silicon, exporting 85% of its product to overseas markets.[117] Although the company primarily supplies silicon metal to the alloys and chemicals market, it has the capacity to produce metallurgical grade silicon for the solar sector if the right quality of HPQ feedstock is used. Currently Simcoa's product is reported to be at 99.4% purity with contaminants of iron, phosphorus, titanium, aluminium and calcium. Simcoa benefits from co-location and vertical integration with its quartz mine at Moora WA, and utilises waste wood from local logging and sawmill operations to produce silicon metal.[118] Simcoa also sells 13,000 tonnes of by-product silica fume which improves overall project economics.[117]

The subsequent step involves the production of solar-grade polysilicon (i.e. 6N–11N purity).[119] More than 90% of global polysilicon is produced via the 'Siemens' process which involves the hydrochlorination of silicon metal, purification via fractional distillation and deposition onto silicon seed rods which are then broken into pieces for further processing.[120] Polysilicon can also be produced via the Fluidised Bed Reactor (FBR) method, which currently makes up 3–5% of market share.[121] The remaining method, 'upgraded metallurgical silicon' (UMG), was discontinued in 2020.[122]

Polysilicon production is comparatively more complex than silicon metal production, and while there is an abundance of IP (particularly for FBR) and know-how overseas, the dominant processes are relatively well known.[123] The key challenge is the price sensitivity of polysilicon production to capital, labour and energy costs as well as relationships with equipment suppliers.[121]

These challenges are reflected in recent global market shifts, where polysilicon production was largely dominated by US, EU and Japanese companies until 2005. The market segmentation has since changed following the emergence of Chinese manufacturers such as Xinte, Daqo and Tongwei who have scaled-up and advanced their technologies to achieve a high-purity product suitable for monocrystalline wafer production.[124] Note that issues affecting polysilicon production in China in 2020 resulted in a 10% increase in wafer costs.[125]

With silicon as the main driver of a local solar production industry, Australia may be well placed to continue to expand its major metals production, namely copper (conductor/module) and aluminium (frame) which are inputs at the cell and module manufacturing stages of the value chain.

2.1.2 Manufacturing

While there is currently limited manufacturing activity in Australia, solar PV represents one of the primary energy technologies with sufficient local demand to de-risk investment. For instance, Australia leads the world in installed solar PV per capita, has experienced a greater than tenfold increase in installed megawatt capacity since 2011 and is projecting the cumulative number of installed systems to rise from 2.08 million in 2018 to 5.2 million by 2050.[126] These forecasts do not include renewable energy export opportunities such as the Asian Renewables Energy Hub.[127] Further, with the poor viability of recycled silicon (see Section 2.1.3) and many of the first wave of solar installations expected to reach the end of their asset life in the next decade, ongoing demand will largely need to be met by virgin rather than recycled materials.

117 Simcoa (2020) Company. Viewed 13 October 2020, <https://www.simcoa.com.au/company>.

118 Anti-Dumping Commission (2014) Investigation 237 Alleged dumping and subsidisation of silicon metal exported from the People's Republic of China.

119 99.9999%–99.9999999% purity. Monocrystalline cells require a higher grade than polycrystalline cells. The semiconductor market requires higher purity, from 9N-11N and above.

120 Woodhouse M et al. (2018) Crystalline Silicon Photovoltaic Module Manufacturing Costs and Sustainable Pricing: 1H 2018 Benchmark and cost Reduction Road Map. NREL, US; Bernreuter J (2020) Polysilicon Production Processes. Viewed 13 October 2020, <https://www.bernreuter.com/polysilicon/production-processes/>

121 Woodhouse M et al. (2018) Crystalline Silicon Photovoltaic Module Manufacturing Costs and Sustainable Pricing: 1H 2018 Benchmark and cost Reduction Road Map. NREL, US.

122 Bernreuter J (2020) Polysilicon Production Processes. Viewed 13 October 2020, <https://www.bernreuter.com/polysilicon/production-processes/>

123 Woodhouse M et al. (2018) Crystalline Silicon Photovoltaic Module Manufacturing Costs and Sustainable Pricing: 1H 2018 Benchmark and cost Reduction Road Map. NREL, US; Maurits JEA (2014) Chapter 2.6: Silicon Production. In Seetharaman S (ed). Treatise on Process Metallurgy. Volume 3: Industrial Processes, Elsevier.

124 Bernreuter J (2020) Polysilicon Production Processes. Viewed 13 October 2020, <https://www.bernreuter.com/polysilicon/production-processes/>.

125 Vorrath S (2020) Solar developers warned of PV price rise as polysilicon supply troubles hit. Viewed 25 November 2020, <https://reneweconomy.com.au/solar-developers-warned-of-pv-price-rise-as-polysilicon-supply-troubles-hit-54043/>.

126 ARENA, Australian PV Institute (2019) National Survey Report of PV Power Applications in Australia 2019; Green Energy Markets (2020) Projections for distributed energy resources – solar PV and stationary energy battery systems. Report for AEMO June 2020.

127 A build of 26,000 MW of wind and solar PV for the production of green hydrogen for the WA mining sector and energy export to Asian markets; The Asian Renewable Energy Hub (2020) The Asian Renewable Energy Hub. Viewed 27 October 2020, <https://asianrehub.com/>.

The manufacture of solar PV comprises of three primary steps: ingot and wafer production, cell manufacture and module assembly. Australia's comparative strengths with regard to each of these steps are detailed further below.

Ingots and wafers

The first step in the manufacture of solar PV panels involves melting polysilicon feedstock in a crucible to produce ingots which are then cut into wafers. Crucibles, which are only used once before being discarded, are made of fused quartz which also needs to be of a high purity in order to avoid the introduction of additional impurities during the process.[128] Diverting locally produced HPQ to crucible production obviates the need to import these materials from overseas.

Crystallisation of the ingot is achieved via the Czochralski method for mono-crystalline wafers, or Directional Solidification for multi-crystalline wafers. Both wafer types are predominantly produced in China (97%) and subsequently exported to cell manufacturers.[129] Importantly for Australia, numerous global suppliers can provide the equipment and skills needed.[130] However, there is still likely to be considerable competition from other low-cost manufacturing jurisdictions, particularly across South East Asia.

Cell manufacture

Cell manufacture involves further treatment of the wafer, layering, followed by screen-printing (i.e. metallisation) of aluminium and silver (or copper) on each side. Labour costs, combined with the price of the wafer, are largely responsible for discrepancies in price between high and low cost manufacturing countries.[130] The continued roll out of automated processes will therefore play a significant role in ensuring cost competitiveness in Australia. However, a more important way to improve the competitiveness of locally manufactured solar PV is through the continued development of units with higher electrical conversion efficiencies and reduced degradation rates. While Australia has historically been a world leader in solar PV research and development (e.g. PERC), this IP has generally been commercialised offshore. However, emerging companies such as SunDrive, who received funding from ARENA in late 2020, have the potential to reverse this trend.

Case Study: SunDrive Solar[131]

SunDrive Solar, a UNSW spinout based in Wollongong, is providing innovative solutions related to solar cells and underlying manufacturing processes. The company builds on existing technologies via improvements in cell efficiencies, cost and degradation rates by replacing silver with cheaper and more easily sourced copper. Use of copper also enables lower temperature metallisation which enables use of thinner wafers without the risk of breakage. To date, SunDrive Solar has secured a grant of $3 million from ARENA in a bid to secure $9 million to finance development of a commercial scale module as well as an automated production line prototype.

Another key area for the production of higher efficiency units is in the development of perovskite tandem cells (discussed further in Section 2.2.2). These cells have most recently achieved cell efficiencies of 29.1%, compared to the 26–28% efficiency of crystalline solar.[132]

Module assembly

Module assembly involves electrically connecting cells to form an array, followed by lamination and encapsulation, framing (typically using aluminium), and connection to a junction box. Global manufacturers typically choose to import wafers and cells for localised module assembly due to the costs embedded in upstream processing. Notably, this step also has the lowest barrier to entry (i.e. readily available equipment, relatively low capital expenditure and most easily automated).[130] There is one established module manufacturer in Australia, Tindo Solar, which has benefitted from a confluence of public investment, local offtake contracts and the integration of low-cost renewable energy into its production facility.

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128 Kearns J (2019) Silicon single crystals. R Fornari (eds.) Woodhead Publishing Series in Electronic and Optical Materials, Single Crystals of Electronic Materials, Woodhead Publishing, 2019. DOI: 10.1016/B978-0-08-102096-8.00002-1; Peng L et al (2020) Effects of melting parameters and quartz purity on silica glass crucible produced by arc method. Engineering Research Express. DOI: 10.1088/2631-8695/ab7683.

129 Woodhouse M et al. (2018) Crystalline Silicon Photovoltaic Module Manufacturing Costs and Sustainable Pricing: 1H 2018 Benchmark and cost Reduction Road Map. NREL, US; Bernreuter Research (2020) Solar Value Chain. Viewed 27 October 2020, <https://www.bernreuter.com/solar-industry/value-chain/>.

130 Woodhouse M et al. (2018) Crystalline Silicon Photovoltaic Module Manufacturing Costs and Sustainable Pricing: 1H 2018 Benchmark and cost Reduction Road Map. NREL, US.

131 ARENA (2020) Australian start-up leading the way on next generation solar cells. Viewed 27 October 2020, <https://arena.gov.au/news/australian-startup-leading-the-way-on-next-generation-solar-cells/>

132 NREL (2020) Best Research-Cell Efficiency Chart. Viewed 27 October 2020, <https://www.nrel.gov/pv/cell-efficiency.html>.

Case Study: Tindo solar

Tindo Solar operates a fully automated production line in South Australia, manufacturing polycrystalline and PERC-monocrystalline solar modules from imported cells. Tindo's success can be attributed to early support by the SA Government who mandated that the Tesla Virtual Power Plant[133] trial source panels from Australia.[134] Local offtakes were also secured with Renewables SA, Adelaide City Council and Port Pirie Council and debt financing was provided by the CEFC.[135] Notably, the company has addressed the problem of high energy costs by integrating renewables into their manufacturing plant, entering into a power purchase agreement with their building site owners to operate rooftop solar PV systems for a duration of 15 years, and on-selling the excess electricity.[136]

2.1.3 Recycling

Solar PV panels and associated equipment are expected to generate a cumulative 60–70 Mt of waste globally by 2050.[137] For Australia in particular, it is estimated that more than 100,000 t of solar panels will enter the waste stream by 2035.[138]

Existing approaches to solar PV recycling involve dismantling, shredding and sorting materials. This allows for recovery of primarily low value materials which are used in glass packaging, scrap metals and construction and road aggregates. While it is theoretically possible to domestically cast new silicon ingots, metals and dopant layers, it will require a series of emerging separation technologies that are yet to be commercialised at scale (discussed in Section 2.2.2). The purity of the recovered material will dictate whether this is suitable for high or low grade applications.[139]

Thus despite the anticipated volumes, the economic viability of solar PV recycling in the long-term remains unclear. Investment decisions are therefore more likely to be driven by robust product stewardship programs. However, to date there are no guidelines or incentives designed to manage solar PV waste and re-use of materials (i.e. solar PV is listed as a priority under the Product Stewardship Act but recycling guidelines are yet to be implemented). Further, Australia currently has little to no use for recovered silicon due to the lack of onshore refining facilities.

Australia currently has one solar panel recycling facility operated by Reclaim PV in SA. In collaboration with universities, manufacturers and waste management companies, the company has tested different processing methods in anticipation of forthcoming stewardship programs and plans to scale up to 100,000 panels per year.[140] Reclaim PV recently settled on a controlled pyrolysis process for panel separation (i.e. lower energy and CO_2 intensity than conventional pyrolysis), followed by silver recovery (chemical processing) and silicon refining to feed back into the silicon value chain.[141]

2.2 Value chain specific investment priorities

2.2.1 Commercial

Developing local high-purity quartz production

With a number of deposits already identified, there is potential for Australia to position itself as a key supplier of HPQ. However, one of the primary barriers to market entry relates to the strict mine output standards and specifications due to potential trace contaminants within the quartz and their impact on end products. As mentioned, industry benchmark standards are set by Sibelco's IOTA® HPQ product and different grades exist for crucible production, crucible lining, and semiconductor materials for solar and adjacent industries.[142] The challenge is greater in the Australian context when considering that most Australian HPQ resources are prospective and certification of grade consistency and mine lifetimes will be needed to secure investment.

133 The South Australian Tesla Virtual Power Plant connects a network of solar-powered homes, employing Tesla Powerwall batteries and management systems to charge or discharge the grid.

134 Parkinson G (2018) Tindo Solar, small retailers, to win big from Tesla virtual power plant. Viewed 14 October 2020, <https://reneweconomy.com.au/tindo-solar-small-retailers-to-win-big-from-tesla-virtual-power-plant-68090/>.

135 TSBE (2020) Tindo Solar. Viewed 14 October 2020, <https://www.tsbe.com.au/node/48226>; CEFC (2014) CEFC to expand access to solar PV for households and businesses. Viewed 14 October 2020, <https://www.cefc.com.au/media/media-release/cefc-to-expand-access-to-solar-pv-for-households-and-businesses/>.

136 Schneider Electric (2014) Tindo Solar Case Study. Viewed 13 October 2020, <https://solar.schneider-electric.com/wp-content/uploads/2014/10/conext-tl-tindo-solar-case-study_eng.pdf>.

137 Weckend S et al. (2016) End-of-life management: Solar Photovoltaic Panels. IRENA, Belgium.

138 Dudley M et al. (2019) PV Systems Stewardship Options Assessment Second Phase. Stage Eight – Final Report. Sustainability Victoria, Australia.; Sustainability Victoria (2020) National approach to manage solar panel, inverter and battery lifecycles. Viewed 14 October 2020, <https://www.sustainability.vic.gov.au/About-us/Research/Solar-energy-system-lifecycles#:~:text=Photovoltaic%20(PV)%20systems%2C%20 including,Australia's%20waste%20stream%20by%202035>.

139 Heath GA et al. (2020) Research and development priorities for silicon photovoltaic module recycling to support a circular economy. Nature Energy. DOI: 10.1038/s41560-020-0645-2.

140 Filatoff N (2019) Australia's first solar-panel recycler plans to help green the full life cycle of components. PV Magazine. Viewed 14 October 2020 <https://www.pv-magazine-australia.com/2019/01/18/australias-first-solar-panel-recycler-plans-to-help-green-the-full-life-cycle-of-components/>.

141 Reclaim PV (2021) Recycling Process. Viewed 14 January 2021 <https://www.reclaimpv.com/our-recycling-process/>.

The establishment of local and globally recognised certification labs will therefore be an important enabler of a local HPQ industry. Such a model has been implemented by Sibelco who operate a laboratory in Spruce Pine, as well as and stand-alone pilot plant to simulate and optimise processes for production of HPQ.[143]

Co-location (silicon metal)

As mentioned, use of biomass derived charcoal as a reductant in metallurgical silicon production represents an important comparative advantage for Australia. However, given that carbonaceous reductants represent a material cost input to metal production, co-location with HPQ mining and processing should be pursued where possible in order to limit transport costs.[144] This is particularly the case where there is a reasonably proximate waste biomass feedstock available (as per the Simcoa example). Where dedicated biomass crops are required, partnership with suppliers should be agreed upon early given that it can take approximately 5 years for sufficient growth to occur.

Vertical integration

Should economically viable HPQ deposits be realised, vertical integration through to polysilicon is another important enabler of the upstream portion of the solar PV value chain. In contrast to silicon metal (~$3,500/t), polysilicon is a higher value intermediate product ($9,000/t in 2019 down from $16,000/t in 2015).[145] This can de-risk investment in local HPQ resources by localising demand and increase economies of scale by servicing both the solar PV and other semiconductor markets. It also furthers the potential for domestic wafer production.

In line with the objective of producing high efficiency cells in Australia, proponents should target the upper range of polysilicon purity (i.e. 9–11N). This could also enable Australia to expand into the broader electronics semiconductor market which requires similar purity levels. Note that both the Siemens or FBR process may be used and decisions regarding the use of each is likely to involve a trade-off between capital and energy costs (i.e. FBR has a higher capital cost but is a continuous process that requires approximately half as much energy).[146]

Investment decisions relating to preferred processing methods are also likely to be driven by opportunities to licence IP or partner with established global polysilicon producers. A focus on polysilicon in Australia should also increase the scope for ongoing development of alternative methods of production that have a reduced environmental impact (discussed further in Section 2.2.2).

2.2.2 RD&D

Emerging polysilicon production processes

Siemens and FBR are expected to remain the dominant methods of polysilicon production in the coming years.[147] However, given their adverse environmental impact, there are a number of alternatives that show potential for sustainable production without incurring a cost premium once commercially mature.

One example is the ‘new silane process’ where ethanol is reacted with silicon metal using a copper-based catalyst. Advantages of this process include the recyclability of ethanol, lower process temperature (i.e. 180°C) and pressure, as well as higher yields.[148] This process is still in the early stages of development with effort needed to improve product selectivity.[148]

Novel ‘sand-to-silicon’ processes that overcome the energy and toxicity issues associated with mature reduction and chemical purification methods are also being explored. One example is silica depolymerisation (breaking long-chained molecules into smaller ones) using organic alcohols to produce silicon-based chemicals. Recent breakthroughs in this technology have led to greater control over the ratios of reactants and improved yields.[149]

142 Sibelco (2019) IOTA® High Purity Quartz. Viewed 21 December 2020, <https://www.sibelco.com/iota-high-purity-quartz/>; Verdant Minerals (2013) Silica and High Purity Quartz: Industry and Product Background Briefing Note. Viewed 28 October 2020, <http://www.verdantminerals.com.au/sites/default/files/PDF's/Presentations/About%20Silica%203.pdf>.

143 Sibelco (2019) IOTA® High Purity Quartz – Capabilities. Viewed 21 December 2020, <https://www.sibelco.com/iota-high-purity-quartz-capabilities/#research-development>.

144 Chen Z et al. (2017) A Study of the Performance of submerged Arc furnace Smelting of Industrial Silicon. Silicon. DOI: 10.1007/s12633-017-9584-3.

145 Silicon metal prices derived from 5 year average (USGS Mineral Commodity Summaries (2015–2020 publications), polysilicon prices from yearly average spot price; Berneuter J (2020) Polysilicon Price Trend. Viewed 22 December 2020, <https://www.bernreuter.com/polysilicon/price-trend/#chart-closer-view-monthly-polysilicon-spot-price-average-from-2014-through-2019>.

146 Powel DM et al. (2015) The capital intensity of photovoltaics manufacturing: barrier to scale and opportunity for innovation. Energy & Environmental Science. DOI: 10.1039/C5EE01509J; Woodhouse M et al. (2018) Crystalline Silicon Photovoltaic Module Manufacturing Costs and Sustainable Pricing: 1H 2018 Benchmark and cost Reduction Road Map. NREL, US; RECSilicon (2020) REC Silicon’s fluidized bed reactor (FBR) process. Viewed 22 December 2020, <http://www.recsilicon.com/technology/rec-silicons-fluidized-bed-reactor-process/>.

147 VDMA (2020) International Technology Roadmap for Photovoltaic. Eleventh Edition, April 2020.

148 Chigondo F (2018) From Metallurgical-Grade to Solar-Grade Silicon: An Overview. Silicon. DOI: 10.1007/s12633-016-9532-7.

149 Maldonado S (2020) The Importance of New “Sand-to-Silicon” Processes for the Rapid future Increase of Photovoltaics. DOI: 10.1021/acsenergylett.0c02100.

High efficiency cells

As mentioned, continued improvements in solar cell conversion efficiencies will assist Australian proponents in providing a competitive LCOE despite paying a premium for locally sourced intermediate products. For example, should degradation issues be overcome, tandem silicon perovskite cells represent an opportunity to achieve an additional step change improvement in efficiencies (as discussed in Section 2.1.2 Part II).

Case Study: Tandem crystalline silicon and perovskite cells

Integrating perovskite and crystalline silicon cells could enable cell efficiencies of >30% to be achieved.[150] Leading perovskite tandem efficiency lab scale records are currently held by HZB (Germany, 29.1%) and Oxford PV (UK, 28%).[151] The latter has recently partnered with Meyer Bruger (an equipment supplier) with the intention of installing a manufacturing line to produce tandem heterojunction solar cells in 2021.[152] Notably, heterojunction cells are less mature than PERC and will require new manufacturing infrastructure.[153]

Conversely, in Australia, CSIRO is leading efforts to integrate perovskite with PERC cells given their more widespread manufacture. The approach is to coat the surface with the perovskite material in a way that conforms with the texture of the silicon layer. It should be noted that Sundrive's high efficiency silicon cell technology is amenable to integration with perovskite. The University of Sydney and the University of New South Wales have also recently developed an encapsulation solution that is low-cost and can help minimise degradation due to heat and humidity.[154]

Improvements in module design can also enable a more competitive LCOE. As an example, 'bifacial cells' allow light to enter through the front and rear of the cell. This can improve the efficiencies of PERC cells, particularly when combined with multi-busbars (a novel design for metallised strips printed on the cell), as well as reduce metal consumption and resistance losses.[155] While bifacial cells are expected to achieve a 70% global share in the next decade, further RD&D is required to overcome current challenges relating to weight and cost.[156]

Higher efficiency cells and modules also increase the scope for implementation of other balance of plant components that can improve overall performance. For instance, whereas single and dual axis-tracking has traditionally been prohibitive due to the associated capital cost, this can be amortised to a greater extent through higher system efficiencies and improved energy output.

Recycling

Efficient separation of the encapsulant from the layers of the module will be one of the primary enablers of high value materials recovery in solar PV recycling. In order to do this, R&D efforts are currently ongoing to determine whether thermal (e.g. pyrolysis), mechanical (e.g. hot-knife cutting) or chemical (e.g. organic solvents) treatment is the preferred method.[157] Each option comes with trade-offs relating to unit throughput as well as chemical and energy intensity.

Longer-term, solar PV recycling can be improved by designing solar panels that are easy to disassemble. Examples of this include double encapsulation using non-adhesive films, substituting the encapsulation material with alternative thermoplastics, and using vacuum pressure to avoid soldering and lamination.[158] However, significant effort is still required to ensure that these alternative designs do not materially increase panel capital costs.[158] Technical R&D should be coupled with techno-economic and environmental analyses, as well as modelling of various aspects of the waste management system (e.g. collection).

150 Ho-Bailie A and Green M (2019) High-Efficiency Silicon-perovskite tandem cells and modules: Demonstration and commercial evaluation. Project results and lessons learnt. <https://arena.gov.au/assets/2019/10/high-efficiency-silicon-perovskite-tandem-cells-modules-demonstration-commercial-evaluation.pdf>.

151 Efficiencies at the research-cell level (i.e. lab); NREL (2020) Best Research-Cell Efficiency Chart. Viewed 15 December 2020, <https://www.nrel.gov/pv/cell-efficiency.html>.

152 Oxford PV (n.d.) Tandem Cell Production. Viewed 15 January 2021 <https://www.oxfordpv.com/tandem-cell-production>.

153 Fischbeck G (2017) What Comes After PERC? PV Magazine. Viewed 22 December 2020, <https://www.pv-magazine.com/features/what-comes-after-perc/>; VDMA (2020) International Technology Roadmap for Photovoltaic. Eleventh Edition, April 2020.

154 Shi L et al. (2020) Gas chromatography – mass spectrometry analyses of encapsulated stable perovskite solar cells. Science. DOI: 10.1126/science.aba2412; Readfearn G (2020) Australian researchers claim world first in global race to develop better solar panels. The Guardian. Viewed 27 October 2020, <https://www.theguardian.com/australia-news/2020/may/22/australian-researchers-claim-world-first-in-global-race-to-develop-better-solar-panels>

155 IRENA (2019) Future of solar photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects, International Renewable Energy Agency, Abu Dhabi; Braun S et al. (2013) The multi-busbar design: an overview. Energy Procedia. DOI: 10.1016/j.egypro.2013.11.092; Shravan K and Chunduri K (2019) Advanced solar module technology – The time for a new generation of solar modules has come. Taiyang News.

156 VDMA (2020) International Technology Roadmap for Photovoltaic. Eleventh Edition, April 2020.

157 IEA (2018) End-of-life management of Photovoltaic Panels: Trends in PV Module Recycling Technologies. International Energy Agency, US.

158 Deng R et al. (2019) A techno-economic review of silicon photovoltaic module recycling. Renewable and Sustainable Energy Reviews. DOI: 10.1016/j.rser.2019.04.020.

3 Wind

3.1 Value chain opportunities

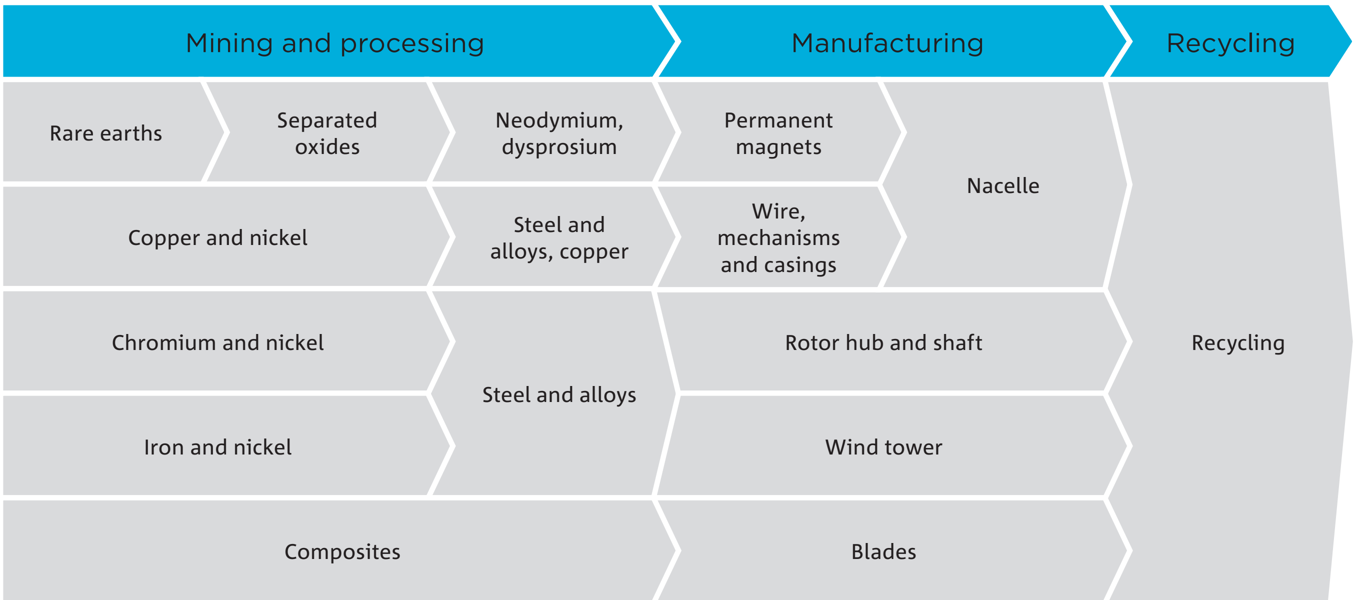

Figure 14: The direct-drive wind turbine value chain

3.1.1 Critical minerals mining and processing

Nacelle (Rare earth elements)

The wind sector represents a relatively small market for Neodymium and Praseodymium (NdPr) compared to EVs (discussed in Section 7) and other applications across defence and information technology (IT). However, forecast deployment of turbines both in Australia and overseas suggests that it could still be an important source of demand for Australian sourced REEs. The following subsections therefore assess the potential for Australia to develop a permanent magnet value chain.

Intermediates to Rare Earth Oxides (REO)

Post extraction, REEs are concentrated via various floatation and separation processes.[159] While REEs may then be sold in concentrate form, product value increases significantly when separated into individual REOs (i.e. 99.9% purity oxides).[159] Primarily due to their similar chemical properties, separation of REOs is a capital and energy intensive process.[160] Further, China's dominance over REO production has stifled investment in other countries by reducing scope for commercially competitive offtake agreements. For instance, as at March 2018, the basket price of REOs produced by Lynas Rare Earths in Malaysia was 24% higher than China.[161]

159 Shih J et al. (2012) The Supply Chain and Industrial Organization of Rare Earth Materials: Implications for the US Wind Energy Sector. Resources for the Future, USA.

160 ATIC (2020) Australian Critical Minerals Prospectus 2020. Department of Industry, Science, Energy and Resources, Australia.

161 Hastings Technology Minerals (2018) Future Producer of Neodymium & Praseodymium to the Permanent Magnet Industry: Investor Present May 2018. Viewed 15 January 2021, <https://media.abnnewswire.net/media/ct/presentations/rpt/ASX-HAS-6A882650.pdf>.

For Australia, investment in REO production is therefore likely to be driven first and foremost by a strategic need to diversify REE supply chains as opposed to pure economics. An example of this strategic diversification may be seen in the September 2020 US Executive Order addressing the critical nature of the REE supply chain to reduce the threat to national security.[162] However, this will not necessarily translate into the development of a REO facility in Australia despite the existing resource base. For instance, both Japan and the US have invested in Australian company Lynas Rare Earths, who extract REEs from a mine in WA but are expected to continue REO production in Malaysia.[163]

Case Study: Lynas Rare Earths

Operating out of the Mount Weld deposit in WA, Lynas Rare Earths is the largest producer of rare earth concentrates in Australia. This deposit is comparatively high grade, with neodymium and praseodymium both mined. Lynas began construction of their Advanced Material Plant in 2008 in Malaysia,[164] and produced ~15,000t of REO in financial year 2019/20.[165]

In 2020 however, a change in the Malaysian licencing requirements, driven by local disapproval over release of low radioactive waste as part of the initial cracking and leaching of the ore concentrate,[164] has forced Lynas to relocate this first stage of processing concentrates back to Australia.[166] Lynas has selected Kalgoorlie in WA as the site for their cracking and leaching plant which is expected to be operational in 2023.[167]

The Japanese Government has recently continued its long term financial support of Lynas, demonstrating robust international partnerships.[168] Further, as of January 2021, Lynas has been contracted by the US to build a commercial REE separation plant in Texas.[169]

At present there are number of emerging companies focused on the development of REO production in Australia, namely Arafura Resources, Hastings Technology Metals and Australian Strategic Materials (ASM). Northern Minerals is another Australian company piloting extraction and processing of heavy REE at Browns Range.[170]

Metals

Metallisation involves the electrochemical reduction of separated REOs (i.e. removal of oxygen) to high purity (99.99%) RE metals. REOs are extremely stable in their oxide form which increases the difficulty of this process.[171] However, production of metals is comparatively straightforward given that it is not ore specific, requiring less bespoke processing techniques.[172] ASM is one Australian company focused on the production of high purity metals through its subsidiary Ziron Technology who is developing a less energy intensive, high-purity metallisation process.[173]

Case Study: Australian Strategic Materials[174]

ASM is developing the Toongi Deposit at their Dubbo Project to extract REEs. ASM's focus is on extraction of REE all the way through to production of high-purity neodymium, praseodymium, terbium and dysprosium metals. The separation, purification and metallisation of oxides will use technology developed by Zircon Technology. Although the pilot plant for this technology is in South Korea, there is potential for the metals processing plant to be deployed alongside the Dubbo Project site in Australia.

162 The White House (2020) Executive Order on Addressing the Threat to the Domestic Supply Chain from Reliance on Critical Minerals from Foreign Adversaries.

163 Schmid M (2019) Mitigating supply risk through involvement in rare earth projects: Japan's strategies and what the US can learn. Resources Policy. DOI: 10.1016/j.resourpol.2019.101457.

164 Tengku Ismal TH et al. (2016) Local community acceptance of the rare earth industry: the case of the Lynas Advanced Materials Plant (LAMP) in Malaysia. Environment, Development and Sustainability. DOI: 10.1007/s10668-015-9675-5.

165 Lynas Corporation (2020) Lynas Corporation AGM Presentation. Viewed 15 January 2021, <https://www.lynascorp.com/wp-content/uploads/2020/11/2020-AGM-presentation-26-Nov-2020-1-JP.pdf>.

166 Office of the Chief Economist (2019) Resources and Energy Quarterly: December 2019. Department of Industry, Innovation and Science, Australia.

167 Lynas Corporation (2020) Lynas selects Kalgoorlie for new cracking and leaching plant. Viewed 10 January 2021, <https://www.lynascorp.com/wp-content/uploads/2019/12/191209-Lynas-Selects-Kalgoorlie.pdf>.

168 Lynas Corporation (2020) Reconfirmation of JARE's long term support for Lynas. <https://www.lynascorp.com/wp-content/uploads/2020/08/200813-Reconfirmation-of-JAREs-Long-Term-Support-for-Lynas-2097316.pdf>.

169 Lynas Corporation (2012) Lynas signs contract to build US light rare earths separation facility. Viewed 2 February 2021, <https://www.lynascorp.com/wp-content/uploads/2021/01/210122-LRE-Separation-Facility-2167273.pdf>.

170 Northern Minerals (2020) Browns Range. Viewed 13 October 2020, <https://northernminerals.com.au/browns-range/>.

171 Abbasalizadeh A et al. (2017) Electrochemical Extraction of Rare Earth Metals in Molten Fluorides: Conversion of Rare Earth Oxides into Rare Earth Fluorides Using Fluoride Additives. Journal of Sustainable Metallurgy. DOI: 10.1007/s40831-017-0120-x.

172 Roskill (2019) Rare Earths Outlook to 2029: Nineteenth Edition.

173 Australian Strategic Materials (2020) ASM Produces Key Heavy Rare Earth Dysprosium Metal in Korea. Viewed 5 January 2021, <https://asmd.irmau.com/site/PDF/a5aaf172-a553-46b8-9bae-0169c63b5e7c/KEYHEAVYRAREEARTHDYSPROSIUMMETALPRODUCEDINKOREA>.

174 ASM (2020) About the Dubbo Project. Viewed 2 November 2020, <https://asm-au.com/projects/dubbo-project/>.

Alloys and magnets

This involves the addition of Iron (Fe) and Boron (B) to produce NdFeB magnet powders which may also contain dysprosium and other traces of elements such as terbium to optimise performance at higher temperatures.[175] These powders are then aligned to orient the magnetic field and are subsequently shaped.[176] Notably, NdFeB magnet IP is largely held by Japanese company, Hitachi, who licence the technology to various magnet manufacturers.[177] Although many relevant patents are set to expire, Australia would still need to partner with overseas manufacturers to create local magnet capabilities for wind turbines. There are five permanent magnet manufacturers outside of China, one located in Europe and the remainder in Japan.[178,179]

Nacelle (copper and nickel)

Copper wiring is used in the generator and power conductor and nickel alloys are used in other nacelle components including the generator and main frame.[180] Well-established mining and processing of these minerals can be leveraged for wind turbines given that there are no specialised metallurgical processing technologies required.

Rotor hub (chromium and nickel)

Chromium is used as an alloy with nickel and steel to form the rotor hub and shaft of all wind turbines. As discussed in Section 2.2 Part I, while Australia has chromium resources, significant investment is required to restart mining and primary processing. Further, although this chromium alloy is conventional and therefore not subject to IP barriers, there is currently no local production in Australia.

3.1.2 Manufacturing

There is potential to develop domestic manufacturing supply chains to support both expected local deployment of wind energy (53 GW to 2050) and a potential hydrogen export industry. Although significant improvements have been realised in the import/export of wind turbine components, their nature and size makes them logistically more challenging and costly than technologies with a higher packing density such as solar PV panels.

Wind turbine components include nacelles, rotor hubs, blades and towers and Australia's potential to develop manufacturing capabilities with respect to each is assessed further below.

Nacelle

The nacelle houses both the permanent magnet generator (direct-drive) or gearbox (geared turbines), as well as the power converter and monitoring and control equipment.[181] The internal components of a nacelle are high value and complex. In contrast, the nacelle cover, which is made of composite materials, faces considerably less IP barriers.[182]

Permanent magnets represent the primary IP associated with nacelle assembly for direct-drive turbines in particular. Similarly, power converters are highly design specific given their role in reducing energy losses between the generator and transmission infrastructure and in optimising overall performance.[183]

Local manufacture is therefore likely to require a partnership with an international OEM or third party magnet and generator suppliers. Depending on the maturity of the turbine, the IP for permanent magnet generators can be held with either the generator manufacturer or wind turbine OEM.[184] Importantly, to reduce transport costs, assembly of the nacelle typically occurs near the site of deployment which increases the scope for some local production.[185]

175 Ahonen S et al. (2015) Strengthening the European Rare Earth Supply-China – Challenges and Policy Options: A report by the European Rare Earths Competency Network. European Commission, France. <https://hal-cea.archives-ouvertes.fr/cea-01550114/document>.

176 Shih J et al. (2012) The Supply Chain and Industrial Organization of Rare Earth Materials: Implications for the US Wind Energy Sector. RFF, USA. <https://media.rff.org/documents/RFF-Rpt-Shih20etal20RareEarthsUSWind.pdf>.

177 Roskill (2019) Rare Earths Outlook to 2029: Nineteenth Edition.

178 Merriman D (2020) Rare earths: Hitachi Ltd. to sell Hitachi Metals including NdFeB magnet patent and production facilities. Viewed 15 January 2021, <https://roskill.com/news/rare-earths-hitachi-ltd-to-sell-hitachi-metals-including-ndfeb-magnet-patent-and-production-facilities/>.

179 Roskill (2019) Rare Earths Outlook to 2029: Nineteenth Edition.

180 Garcia-Olivares A et al. (2012) A global renewable mix with proven technologies and common materials. Energy Policy. DOI: 10.1016/j.enpol.2011.11.018n.

181 Islam M et al. (2014) A review of offshore wind turbine nacelle: technical challenges and research and developmental trends. Renewable and Sustainable Energy reviews. DOI: 10.1016/j.rser.2014.01.085.

182 Navigant Consulting (2013) US Offshore Wind Manufacturing and Supply Chain Development. Report prepared for the US Department of Energy.

183 Semken SR et al. (2012) Direct-drive permanent magnet generators for high power wind turbines: benefits and limiting factor. IET Renewable Power Generation. DOI: 10.1049/iet-rpg.2010.0191.

184 GLWN (2014) U.S. Wind Energy Manufacturing and Supply Chain: A Competitiveness Analysis. Report prepared for US Department of Energy.

185 Navigant Consulting (2013) US Offshore Wind Manufacturing and Supply Chain Development. Report prepared for the US Department of Energy.

Rotor hub and shaft

The manufacture of rotor hubs and shafts are reported to have comparatively lower IP barriers (than the nacelle) which presents an opportunity for new entrants.[185] Further, OEMs have less stringent requirements on rotor hubs and shafts as these components have minimal impact on the overall performance of the wind turbine.[185] However, as previously mentioned, a lack of existing chromium extraction and alloy production represents the primary barrier to local manufacture of these components.

Blades

Blades are constructed from composite materials, predominantly glass fibre, and are the highest cost component of wind turbines.[186] Traditionally, glass fibre has been favoured by the industry due to reliance on established supply chains with low production costs.

However, as demand for wind energy grows and the industry strives for increased blade lengths, carbon fibre represents the most promising alternative.[187] Carbon fibre, although currently more expensive, reduces the weight of the blade which in turn reduces the cost of other turbine components including towers and foundations.[188] OEMs such as Siemens Gamesa and Vestas are now deploying carbon fibre composites for systems with larger blades.[186]

Australian developments in carbon fibre composites may further the scope for local manufacture of wind turbines. For instance, Carbon Nexus, a local research centre and pilot facility has recently partnered with Vestas to develop advanced carbon fibre materials for wind turbines with greater potential for recycling.[189] The local content requirements of the Victorian Renewable Energy Scheme targets has facilitated this partnership, with Vestas continuing to invest in Victorian manufacturing to support local wind installations.[190]

Tower

Wind towers are predominantly comprised of steel. Although not considered a critical metal, local manufacturing can be leveraged to strengthen the case for a domestic wind turbine industry. Currently, despite transport costs and domestic capabilities, Australian wind installations use both locally manufactured and imported wind towers.[191] Importantly, although specifications may differ between OEMs and with respect to direct-drive versus geared technologies, manufacturers are able to tailor tower production with relative ease.[191] The reduced IP and 'know-how' associated with manufacturing wind towers presents a 'shovel ready' opportunity for investment.

3.1.3 Recycling

With an asset life of 20 to 30 years, a growing number of wind turbines will be taken offline in the coming decades.[192] While materials such as steel and copper make up the majority of turbine weight and have mature recycling strategies, challenges arise in relation to blades and permanent magnets.[193]

Permanent magnets

Permanent magnets may be recycled, reused in their current form, or regenerated into master alloys.[194] However, existing barriers to economically viable recycling include a lack of information about the quantity of REE materials and insufficient collection rates.[195]

Importantly, there is potential for permanent magnets to be recycled using similar hydrometallurgical processes to those used in primary production of RE metals.[196] Therefore, it may be possible to extend processing of these metals to accept both recycled and virgin materials which can help improve project economics.

186 Mishnaevsky L et al. (2017) Materials for Wind Turbine Blades: An Overview. Materials. DOI: 10.3390/ma10111285.

187 Navigant Consulting (2013) US Offshore Wind Manufacturing and Supply Chain Development. Report prepared for the US Department of Energy.

188 Ennis B et al. (2019) Optimized Carbon Fiber Composites in Wind Turbine Blade Design. Report prepared for US Department of Energy.

189 Carbon Nexus (2019) Deakin partners with Vestas to advance composites science. Institute for Frontier Materials, Deakin University. Viewed 7 January 2021, <https://www.carbonnexus.com.au/deakin-partners-with-vestas-to-advance-composites-science/>.

190 Carbon Nexus (2019) Industry collaboration targets turbines. Viewed 22 December 2020, <https://www.carbonnexus.com.au/industry-collaboration-targets-turbines/>.

191 Keppel Prince Pty Ltd (2017) Application for the publication of dumping notes: Wind Towers from the Socialist Republic of Vietnam. Viewed 15 January 2021, <https://www.industry.gov.au/sites/default/files/adc/public-record/001_-_application_-_aust_industry_ottoway_fabrication_pty_ltd_and_keppel_prince_engineering_pty_ltd.pdf>.

192 World Steel Association (2012) Steel Solutions in the Green Economy: Wind Turbines.

193 Beauson J & Brøndsted P (2016) Wind Turbine Blades: An End of Life Perspective. Ostachowicz W, McGugan M, Schröder-Hinrichs JW and Luczak, M (eds.) Mare-Wint: New Materials and Reliability in Offshore Wind Turbine Technology. Springer International Publishing, Switzerland.

194 Master alloys are REEs alloyed with base metals (e.g. aluminium or nickel) and can be used as an additive to alloy production or to improve stability during refining and hardening; Firdaus M et al. (2016) Review of High-Temperature Recovery of Rare Earth (Nd/Dy) From Magnet Waste. Journal of Sustainable Metallurgy. DOI: 10.1007/s40831-016-0045-9.

195 Ahonen S et al. (2015) Strengthening the European Rare Earth Supply-China – Challenges and Policy Options: A report by the European Rare Earths Competency Network. European Commission, France.

196 Firdaus M et al. (2016) Review of High-Temperature Recovery of Rare Earth (Nd/Dy) From Magnet Waste. Journal of Sustainable Metallurgy. DOI: 10.1007/s40831-016-0045-9.

Further, given that the commercial viability of recycling is likely to rely heavily on economies of scale, at least in the first instance it is expected to be driven by technologies with shorter life cycles and higher volumes, such as mobile phones or EV motors.[197] Permanent magnet recycling is therefore more likely to scale independently of the wind sector.

Blades

The majority of wind turbine blades are cut into segments and deposited to landfill, with a small portion ground up for applications in cement production or used as insulation.[198] In addition to a growing number of wind installations, longer blade lengths are also expected to increase pressure on landfill. Further, given that long distance haulage for recycling blades is unlikely to be cost effective, Australia will need to develop optimised blade recycling strategies and processes.[198]

3.2 Value chain specific investment priorities

3.2.1 Commercial

Vertical integration of REE metal production

Deployment of local metal production facilities is arguably the most important enabler of a viable REE processing industry in Australia. By focusing investment on this value chain step, it minimises the need for proponents to compete directly with China with respect to the price of REOs and obviates the requirement for export of those REOs to China for metal processing. In turn, this can de-risk investment in REO facilities, increase scope for mid-tier and junior miners to access capital and further the potential for centralisation of processing assets.

Centralisation of REE metal processing

Centralisation of assets is particularly important in the context of REEs given the number of prospective developers in Australia combined with the current lack of infrastructure supporting downstream processing. Although related to nickel, BHP Nickel West adopted a similar model by deploying a vertically integrated mine, concentrator plant and smelter. The concentrator plant processes ore and concentrate purchased from third parties as well as from Nickel West's four mine sites in WA.[199]

Metallisation facilities represent the most favourable point of centralisation in the REE value chain due to the greater uniformity of input. While centralisation of REO separation facilities may also be considered, this is more challenging when dealing with REE concentrates sourced from different host minerals that are likely to require unique processing specifications (e.g. type and concentration of leaching solution).[200] Further, given the distance between the various REE deposits across WA, NSW, NT and VIC, this option will attract higher distribution costs due to the lower content of valuable product in REE concentrates.[201] Emerging REE mining companies have also invested significant capital and time (some more than 20 years) in developing their orebody specific metallurgical processes.[202]

The case for vertical integration and centralisation of metallisation assets is furthered when considering the potential to recycle permanent magnets via similar hydrometallurgical processes to those used in primary metallisation processes.[203] Note however that there is a risk that centralisation may stifle competition and unfairly prejudice companies seeking to develop their own vertically integrated processes.

197 Yang Y et al. (2016) REE Recovery from End-of-Life NdFeB Permanent Magnet Scrap: A Critical Review. Journal of Sustainable Metallurgy. DOI: 10.1007/s40831-016-0090-4.

198 Beauson J & Brøndsted P (2016) Wind Turbine Blades: An End of Life Perspective. Ostachowicz W, McGugan M, Schröder-Hinrichs JW and Luczak, M (eds.) Mare-Wint: New Materials and Reliability in Offshore Wind Turbine Technology. Springer International Publishing, Switzerland.

199 BHP (2020) Nickel West. Viewed 23 December 2020, <https://www.bhp.com/our-businesses/minerals-australia/nickel-west/>.

200 Xie F et al. (2014) A critical review on solvent extraction of rare earths from aqueous solutions. Minerals Engineering. DOI: 10.1016/j.mineng.2013.10.021.

201 ATIC (2020) Australian Critical Minerals Prospectus 2020. Department of Industry, Science, Energy and Resources, Australia.

202 Treadgold T (2020) Joint Korean-Australian Project Targets China's Rare Earth Control. Forbes. Viewed 4 January 2021, <https://www.forbes.com/sites/timtreadgold/2020/11/09/joint-koreanaustralian-project-targets-chinas-rare-earth-control/?sh=59a6de71224c>.

203 Tunsu C (2018) Chapter 8: Hydrometallurgy in the recycling of spent NdFeB permanent magnets. C Tunsu (ed.) Waste Electrical and Electronic Equipment Recycling: Aqueous Recovery Methods. Woodhead Publishing Series, USA.

3.2.2 Policy/regulatory

Collection and sorting of permanent magnets

As mentioned in Section 3.1.3, although wind turbines contain large volumes of permanent magnet materials, it is widely used electrical products with shorter life cycles (e.g. hard disk drives, DVD players and speaker systems) that are likely to drive investment in magnet recycling in the near term.[203] These products should therefore be the primary focus of permanent magnet product stewardship programs.

As distinct from wind turbines, collection of many of these end-products are dependent on consumer habits and waste flows.[204] As a result, consumer education strategies and consistent regulations will likely be required to prevent products from entering landfill. In the long term, collection rates may improve as wind turbines are taken offline, with greater expectation on asset operators to responsibly manage turbine decommissioning.[203]

Sorting permanent magnets from other components is a substantial cost for recycling, particularly as end-products coming offline are required to be dismantled which leads to high labour costs.[205] Streamlined waste collection may improve the sorting processes and allow more automated disassembly of common end-products. For example, hard disk drives can be disassembled through specific vibration frequencies that loosen the screws while keeping the permanent magnet intact.[204]

3.2.3 RD&D

Reducing REE processing costs

Both extraction of REEs (due to difficulty liberating from associated minerals such as uranium and thorium) and REO separation via solvent extraction are energy intensive processes.[206] Continued developments in metallurgical methods (e.g. froth floatation that exploits differences in hydrophilicity) will therefore be important in achieving further reductions in cost.

For REO separation in particular, alternative solvents which produce less harmful by-products and consequently reduce waste management costs may also be important in the Australian context.[207] However, these alternatives can have high rates of acid consumption during leaching and further improvements in acid recovery rates will therefore be needed.[208]

Recycling permanent magnets

Hydrogen decrepitation can be used to recycle permanent magnets and produce NdFeB powder. However, the presence of contaminants in the resulting product currently prevents direct formation of new permanent magnets.[209] In the event that this barrier is not overcome, existing primary processing technologies may be used to recover rare earth metals from recycled magnets (discussed in Section 3.1.3). Innovative pyrometallurgical technologies should also be considered given their potential to minimise water, chemical and energy requirements. Further, Deakin University has recently developed an electrodeposition recycling technology (using ionic liquids) which also has potential to lower processing costs.[210]

Blade recycling technology

Key requirements for economically viable blade recycling include production of higher value products, reductions in energy intensity and lowering of capital costs for blade cutting and dust management equipment.[211]

As mentioned, Carbon Nexus is also focused on improving the viability of recycling by developing next generation carbon composite blades which have potential to produce higher value secondary materials. Further, as blade waste is estimated to only account for 10% of total composite material waste in 2025, there is potential for advancements in composite recycling for other applications to be subsequently leveraged by the wind sector.[211]

204 Nemeto T et al. (2019) Collection Service and Recycling Technology for Information and Telecommunications Electronics. Hitachi Review 68(5), 125–132.

205 Tunsu C (2018) Chapter 8: Hydrometallurgy in the recycling of spent NdFeB permanent magnets. C Tunsu (ed.) Waste Electrical and Electronic Equipment Recycling: Aqueous Recovery Methods. Woodhead Publishing Series, USA.

206 Torrisi A (2014) Rare earth recycling and recovery: the two sides of the industry. Industrial Minerals, 566 (2), 39–43; Perio LT and Mendez GV (2013) Material and Energy Requirement for Rare Earth Production. JOM. DOI: 10.1007/s11837-013-0719-8.

207 Shin S et al. (2019) Worker Safety in the Rare Earth Elements Recycling Process the Review of Toxicity and Issues. Safety and Health at Work. DOI: 10.1016/j.shaw.2019.08.005.

208 Lazo D et al. (2017) Treatment of monazite by organic acids I: Solution conversion of rare earths. Hydrometallurgy. DOI: 10.1016/j.hydromet.2017.10.003.

209 Walton A et al. (2015) The use of hydrogen to separate and recycle neodymium–iron–boron-type magnets from electronic waste. Journal of Cleaner Production. DOI: 10.1016/j.jclepro.2015.05.033.

210 Sanchez-Cupido L et al. (2019) Water-Facilitated Electrodeposition of Neodymium in a Phosphonium-Based Ionic Liquid. Journal of Physical Chemistry Letters. DOI: 10.1021/acs.jpclett.8b03203.

211 Wind Europe (2020) Accelerating Wind Turbine Blade Circularity. <https://cefic.org/app/uploads/2020/05/Accelarating-wind-turbine-blade-waste-recycling.pdf>.

4 Concentrated Solar Power (CSP)

4.1 Value chain opportunities

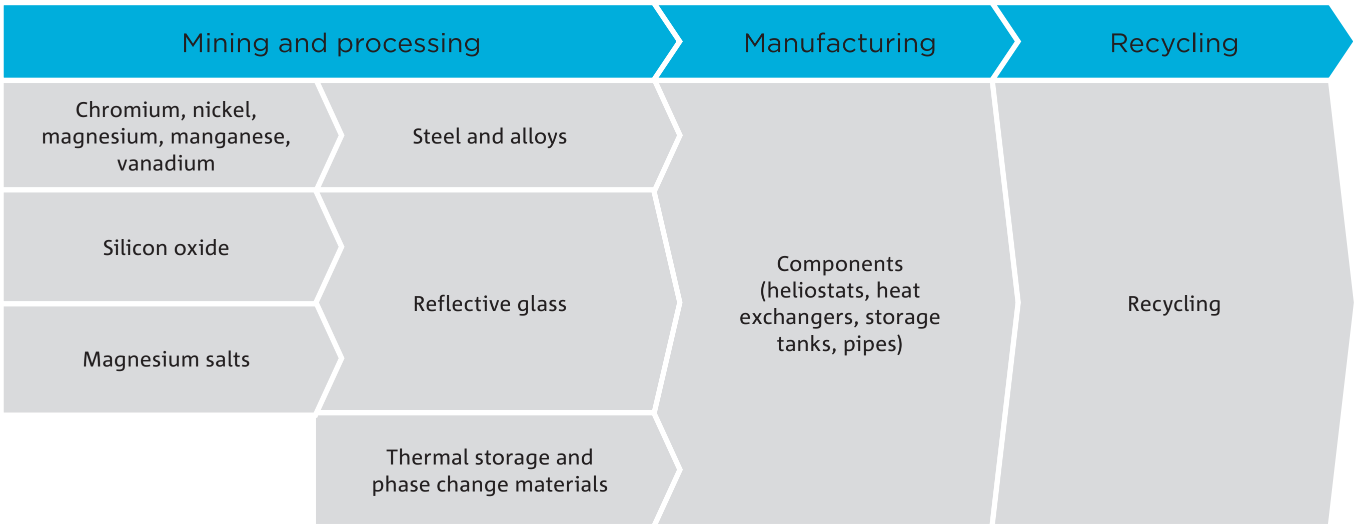

Figure 15: CSP central tower value chain

4.1.1 Critical minerals mining and processing

Chromium, nickel, magnesium, manganese and vanadium may be used in high temperature and support structure steel alloys in CSP. These alloys, which are employed to withstand harsh, fluctuating temperatures and corrosive conditions, are not unique to CSP and are typically used for conventional fossil fuel based thermal energy plants.[212] Common CSP alloys and their functions are set out in Table 3.

With the exception of chromium and vanadium, despite having mature production of the relevant minerals, there is limited domestic manufacturing of the corresponding alloys. However, companies such as Alloy Steel International and Valbruna Australia that produce nickel and magnesium based alloys for the mining sector could be leveraged to support CSP.

Table 3: Use of critical metal alloys in central tower plants[213]

Components	Alloys used
Heliostat supports	Hot-dip galvanised steel; mainly carbon steel (98% iron, 1% carbon, 1% manganese) covered by a 100-micrometre zinc layer.
Heat transfer and storage	Plant receiver, hot salt pipes and hot salt tank: 347H stainless steel (17–19% chromium, 9–13% nickel, 2% manganese, other trace elements).[214] Other molten salt pipes and cold tank: carbon steel.
Heat exchangers	347H stainless steel for high temperatures and carbon steel for low temperatures.
Steam pipes	12% chromium steel at high temperatures and carbon steel at low temperatures.
Steam turbines	High proportion of stainless 9–12% chromium steels, also containing molybdenum, manganese, nickel, vanadium and other trace elements.

212 Nickel Institute (2020) Nickel alloys in oil, gas & power. Viewed 4 January 2021, <https://nickelinstitute.org/about-nickel/nickel-alloys-in-oil-gas-power/>; Haynes International (2020) Power Generation. Viewed 4 January 2021, <http://www.haynesintl.com/markets/power-generation>.

213 Phil E et al. (2012) Materials constraints for concentrating solar thermal power. Energy. DOI: 10.1016/j.energy.2012.04.057.

214 Sandmeyer Steel Company (2014) specification Sheet: Alloy 347/347H. Viewed 4 January 2021, <https://www.sandmeyersteel.com/images/Alloy347-SpecSheet.pdf>.

Rather, these alloys are typically imported (from countries such as Sweden and the US) and demand from both domestic and global CSP deployment is unlikely to provide sufficient incentives for Australia to invest in local production.[215] This is particularly the case given that a number of key CSP markets such as Morocco and Spain have domestic manufacturing and local content requirements to support development. Spain, for example, manufactures around 75–80% of its CSP components.[216]

While silica sand is used to produce reflective glass for collectors or heliostats, this does not rely on the same HPQ deposits required for solar PV. Further, similar to most energy technologies, both aluminium and copper are employed for components such as wiring, turbines, generators and electric motors.

In relation to central tower CSP development, investor confidence in the industry may well be dependent on cost competitive electricity generation while operating at temperatures of approximately 500°C. Once achieved however, this can increase the scope for further development of higher temperature systems (i.e. 800–1000°C) for both electricity and/or process heat applications. At such temperatures, greater challenges arise with respect to material integrity (i.e. strength, creep and fatigue resistance), chemical compatibility and high temperature corrosion resistance, which will require the use of novel high temperature materials and alloys (discussed further in Section 4.2.2).[217]

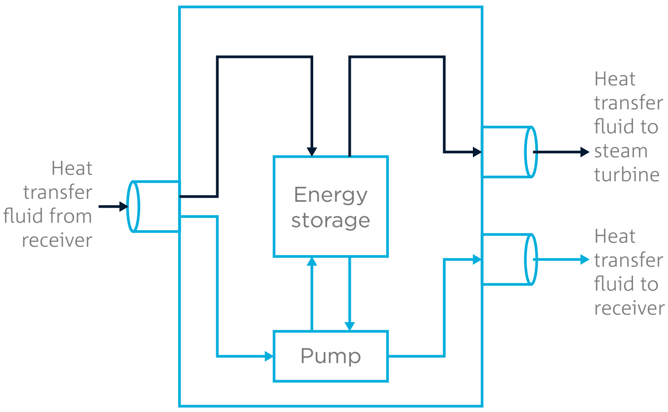

Figure 16: Summary of thermal energy storage systems

Operating at higher temperatures is also likely to further the need for solid state thermal storage systems that may be designed for modular applications such as fringe of grid solutions. These systems store energy by heating or cooling phase change materials (PCM).[218] Notably, these systems comprise of other critical energy minerals such as graphite, aluminium and (a lower level purity) silicon. Importantly, their development is being driven by a series of early stage Australian companies such as 1414 degrees, MGA Thermal, Solastor and Graphite Energy. Given the robust and modular nature of these systems, they can be containerised and shipped offshore.

4.1.2 Manufacturing

Case Study: Vast Solar[220]

Vast Solar is an Australian CSP company that has developed and commercialised its own modular CSP and solar thermal storage systems. In 2018, their 1.1 MW_e pilot plant (and Australia's first grid-connected CSP plant) in Jemalong (NSW) was fully commissioned.[221] Alongside the patented technology and system design, Vast Solar offers project delivery services to coordinate the planning and operation of new CSP plants in partnership with developers and utility providers. This model (i.e. provision of project delivery and plant operation services based on unique IP) is one that could be applied across Australia and overseas.

As previously discussed, a significant proportion of the componentry underpinning a CSP plant has a low level of complexity and can be sourced locally. However, heliostats (i.e. sun concentrating mirrors) have a material impact on cost and operation of the asset and are subject to considerable IP.[219] Some of the leading IP is held by a series of Australian companies and relates specifically to optimising performance and materials required due to the high volumes of these units needed for a single CSP asset and the consequent impact on cost.

Although heliostats have a higher value once assembled, the nature of CSP is that fabricated materials are typically exported to the deployment site and components are

215 Haynes International (2020) Locations. Viewed 4 January 2021, <https://www.haynesintl.com/company-information/locations>.

216 Rampersad G et al. (2018) Industry Development Opportunities for developing Concentrating Solar Thermal Power in Australia. Report prepared for ARENA, Australia.

217 Moghaddam S et al. (2018) Materials compatibility for the next generation of Concentrated Solar Power plants. Energy Storage Materials, DOI: 10.1016/j.ensm.2018.02.023.

218 Pause B (2010) Phase change materials and their application in coatings and laminates for textiles. Smart Textile Coatings and Laminates. DOI: 10.1533/9781845697785.2.236.

219 Chamberlain K (2020) Self-aligning heliostats arrive to slice Concentrated Solar Power costs. Focal Line Solar. Viewed 10 February 2021, <https://flsnova.com/2020/02/12/self-aligning-heliostats-arrive-to-slice-concentrated-solar-power-costs/>.

manufactured locally. This is primarily due to the fact that heliostats occupy large volumes that render pre-assembly and export inefficient. Further, heliostats are fragile which significantly increases the cost of transport. As a consequence, leading Australian CSP developers such as Vast Solar are able to commercialise their IP by designing and constructing assets in conjunction with local material suppliers and developers.

4.1.3 Recycling

The asset life of a CSP plant is typically in the order of 20-30 years and given the nascency of the industry worldwide, there is unlikely to be significant volumes of material to be recycled in the near-term. In addition, most of the embedded metals (e.g. steels, aluminium and copper) and glass have well established recycling processes with high recovery rates.

In Australia, currently almost all stainless steel scrap metal is sent overseas to be recycled and imported back as new steel products.[222] This is unlikely to change as a consequence of developments in CSP. However, given high performance alloy recycling currently lags that of common steels, efforts to deploy local manufacturing of these alloys in the long-term could also involve the development of fit-for-purpose hydro, pyro and electro-metallurgical processes that enable high recovery rates.[223]

4.2 Value chain specific investment priorities

4.2.1 Policy/regulatory

Project pipeline

As mentioned in Part I, CSP is not currently cost competitive with other forms of electricity generation such as solar PV and wind. However, this is partially due to the limited value currently placed on dispatchable thermal energy (as opposed to variable renewable energy) and system inertia required to ensure grid stability and reliability.

In contrast to high volume distributed energy technologies such as batteries and fuel cells, CSP is typically a large-scale centralised asset. Thus, while policy mechanisms such as ‘Contracts for Difference’ can help achieve a competitive LCOE and stimulate investment in CSP, commitment to a pipeline of projects across Australia over the next decade will be needed to de-risk investment in manufacturing supply chains.

4.2.2 RD&D

Thermal energy storage

Solid state thermal energy storage using PCMs poses many advantages over liquids and molten salts. These include reduced costs, wider operating temperatures and no leakage. However, a key drawback associated with PCMs is that they have lower thermal conductivity which restricts the efficient transfer of energy and leads to excessive charge and discharge times.[224] This can be mitigated through the development of ‘thermal conductivity promotors’ (e.g. ‘metal matrix’[225] or foam) and use of alternate metal alloys which typically have varying levels of aluminium.[226] Metal matrix materials are a key focus of Australian company MGA Thermal, who are exploring graphite-based PCMs to operate as both a solar receiver and thermal storage material.[227]

High performance alloys

R&D in next generation alloys is largely dictated by the specific requirements and characteristics of its intended application. In this case, CSP developers may need to engage with metallurgical researchers to specify the characteristics needed to tolerate high temperatures while minimising impact on capital costs.

The emergence of 3D printing of superalloys, already commercially available for industrial use, may also present an opportunity to produce precise componentry for CSP systems. For instance, in 2017, Sandia National Laboratories used 3D printing to produce a prototype solar receiver that comprised of high temperature nickel alloys and alumina. This approach enabled the development of geometric features in the material that increases the solar absorptance of the receiver.[228] Note however that the suitability for 3D printing can vary between alloys.

220 Vast Solar (2020) About Us. Viewed 4 January 2021, <https://vastsolar.com/about-us/>.

221 Vast Solar (2020) Jemalong CSP Pilot Plant 1.1Mwe. Viewed 4 January 2021, <https://vastsolar.com/portfolio-items/jemalong-solar-station-pilot-1-1mwe/>.

222 ASSDA (2019) Recycling. Viewed 4 January 2021, <https://www.assda.asn.au/technical-info/environment-health-and-safety/recycling>.

223 Srivastava R et al. (2014) Resource recycling of superalloys and hydrometallurgical challenges. Journal of Materials Science. DOI: 10.1007/s10853-014-8219-y.

224 Pelay U et al. (2017) Thermal energy storage systems for concentrated solar power plants. Renewable and Sustainable Energy reviews. DOI: 10.1016/j.rser.2017.03.139.

225 Metal matrix materials are composites consisting of a metal and at least one other constituent part.

226 Risuene E et al. (2016) Experimental investigation of Mg-Zn-Al metal alloys for latent heat storage application. Journal of Alloys and Compounds. DOI: 10.1016/j.jallcom.2016.06.222.

227 Copus M et al. (2019) On-sun testing of Miscibility Gap Alloy thermal storage. Solar Energy. DOI: 10.1016/j.solener.2018.11.048.

228 Shemer N (2017) 3D printing enables new high-efficiency CSP receivers. Reuters. Viewed 4 January 2021, <https://www.reutersevents.com/renewables/csp-today/3d-printing-enables-new-high-efficiency-csp-receivers>.

Integration of CSP in minerals processing

While there is potential to integrate CSP into high temperature minerals processing, this has yet to be demonstrated at scale. Global RD&D is currently focused on the feasibility of hybridised solar thermal and fossil fuel-based systems at laboratory and pilot scale. For example, a 2018 pilot study at the Kalagadi manganese sinter plant in South Africa successfully tested the integration of CSP with diesel-fuelled heat systems.[229]

In Australia there are ongoing efforts to integrate CSP into the Bayer process (for alumina production). The University of Adelaide expects that CSP could be integrated for continuous operation with existing refineries and fuel supply systems with minimal modifications required.[230] It is expected that CSP could generate temperatures between 800–1000°C at an approximate cost of AUD$10/GJ.[230]

Case Study: Integrating solar thermal energy into the Bayer process

This ARENA-funded project is led by the University of Adelaide in partnership with Alcoa, CSIRO, ITP Thermal, UNSW and Hatch. Its primary aim is to integrate solar energy into hybrid systems for continuous alumina production.[231]

In 2020, use of a solar reactor in alumina calcination was successfully demonstrated at lab scale with 96% conversion efficiency from receiver to calciner.[232] This is a critical step in alumina production which requires temperatures of 950°C. Other research projects under this partnership include integration of CSP to supply heat for steam generation in bauxite digestion, which typically requires temperatures of up to 300°C, and integration of solar reforming of natural gas, which can increase the energy content of the fuel by 20–30%.[233] It is expected that 29–45% of the energy required for the Bayer alumina process could be derived from concentrated solar thermal technology.[234]

Beam down CSP plants

'Beam down' is an emerging variant of central tower configurations that may further the potential integration of CSP into minerals processing. This technology allows for higher operating temperatures (up to 1300°C) by concentrating solar energy in a two stage process (as shown in Figure 17).[235] Light reflected from heliostats is subsequently reflected vertically in order to further concentrate the energy before it is captured by the receiver.[236]

Additional benefits include minimisation of heat losses and reduced tower costs due to the solar receiver being located on the ground.[237] However, the two stage solar concentration can cause reflection losses and has a higher maintenance requirement to ensure alignment of reflectors.[237] Beyond minerals processing, the technology has other potential commercial applications including the production of hydrogen. This is currently being explored by ARENA in partnership with the Japanese Institute of Applied Energy.[235]

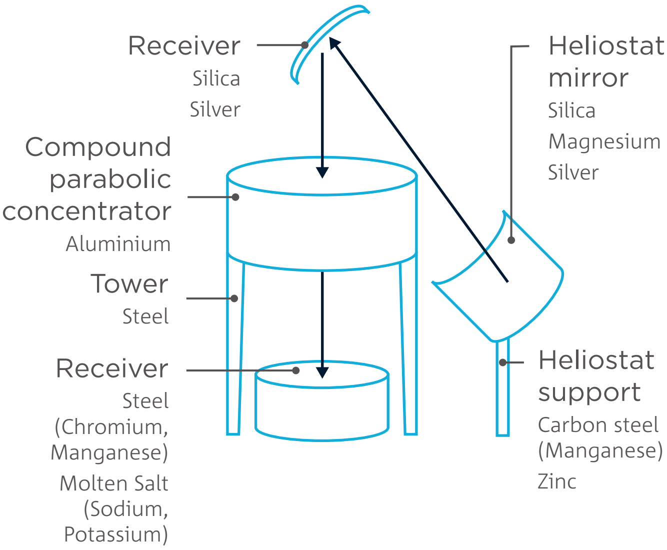

Figure 17: Summary of beam down CSP plants

229 Lubkoll M et al. (2018) Integrating solar process heat into manganese ore pre-heating. 5th Southern African Solar Energy Conference. 25–27 June.

230 The University of Adelaide (n.d.) Solar thermal in the Bayer alumina process. Viewed 13 October 2020, <https://www.adelaide.edu.au/cet/solar-alumina/>.

231 ARENA (2020) Integrating concentrating solar thermal energy. Viewed 12 October 2020, <https://arena.gov.au/projects/integrating-concentrating-solar-thermal-energy-into-the-bayer-alumina-process/>.

232 The University of Adelaide (2020) Commercialising alumina refining using solar heat. Viewed 13 October 2020, <https://www.adelaide.edu.au/cet/solar-alumina/news/list/2020/08/04/commercialising-alumina-refining-using-solar-heat>.

233 Kraemer S (2020) Australian researchers assess the commercial viability of solar alumina calcining. Viewed 12 October 2020, <https://www.solarpaces.org/australian-researchers-assess-the-commercial-viability-of-solar-alumina-calcining/>.

234 The University of Adelaide (n.d.) Solar thermal in the Bayer alumina process. Viewed 13 October 2020, <https://www.adelaide.edu.au/cet/solar-alumina/>.

235 ARENA (2020) Solar Thermochemical Hydrogen Research and Development. Viewed 7 January 2021, <https://arena.gov.au/projects/solar-thermochemical-hydrogen-research-and-development/>.

236 Leonardi E (2012) Detailed analysis of the solar power collected in a beam-down central receiver system. Solar Energy. DOI: 10.1016/j.solener.2011.11.017.

237 Diago M et al. (2020) Net power maximization from a faceted beam-down solar concentrator. Solar Energy. DOI: 10.1016/j.solener.2020.04.061.

5 Batteries

5.1 Value chain opportunities – Lithium-ion batteries

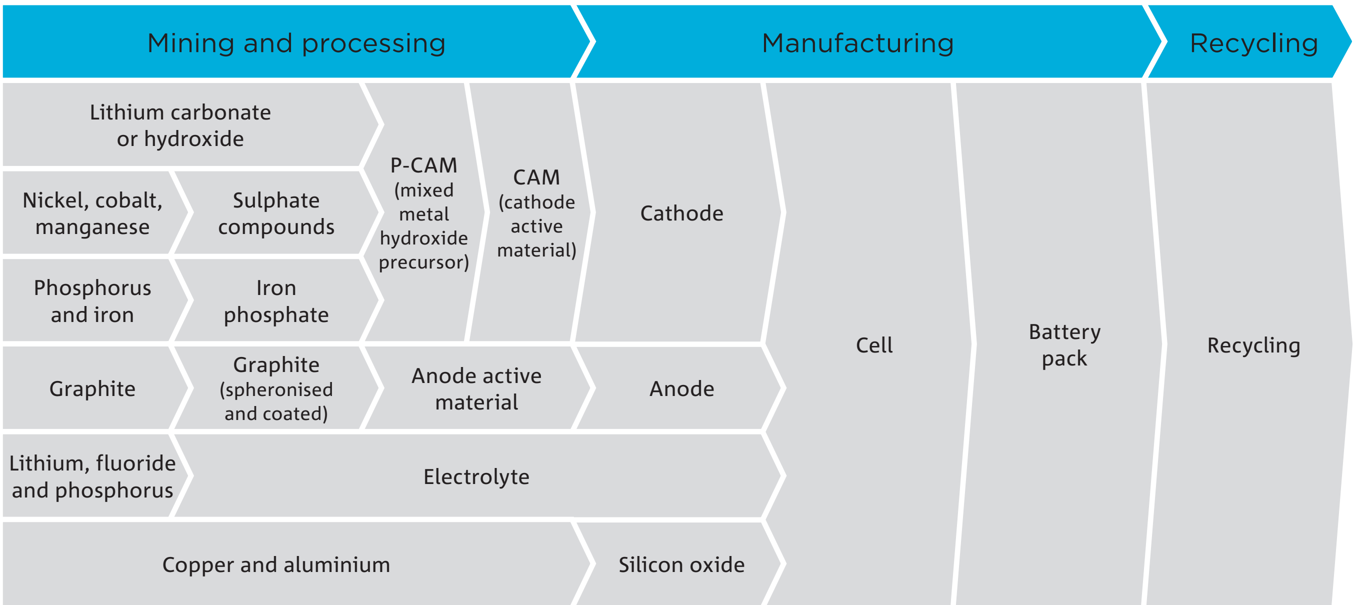

Figure 18: Lithium-ion battery value chain

5.1.1 Critical minerals mining and processing

Cathode (LiNMC)

Australia is well placed to supply many of the raw materials for the various battery chemistries. For LiNMC in particular, as shown in Section 2.2 Part I, lithium, manganese and nickel are considered 'low risk' with respect to the Australian mining industry. Further, the potential for vertically integrated mixed metal hydroxide precursors (P-CAM) and subsequent lithiated cathode active materials (CAM) production is likely to encourage further development in cobalt despite its higher risk profile.[238]

CAM production relies on high purity metals which will require a greater level of investment in nickel, manganese and cobalt than what is typically needed for their respective steel markets. Although there is also currently significant investment being directed towards battery precursor chemicals (i.e. lithium hydroxide, nickel-, manganese- and cobalt-sulphate), commercial viability is likely to depend on the production of high quality materials while minimising cost and environmental impact.[239] Figure 19 sets out the current state of development in Australia.

238 P-CAM for LiNMC consists of a nickel, cobalt and manganese mixed metal powder which is then combined with lithium to produce CAM; FBICRC (2020) Li-ion battery cathode manufacture in Australia: A scene setting project.

239 QUT (2020) Li-ion battery cathode manufacture in Australia: A Scene Setting Project. FBICRC, Australia; FBICRC (2020) The governance of battery value chains: Security, sustainability and Australian Policy Options. FBICRC, Australia.

	Feasibility	Pilot	Commercial
Lithium hydroxide/ lithium carbonate	**ICS** Closed-loop production of $LiHO_2$ from spodumene concentrate	**Lepidico** Li_2CO_3 from mica slurry, DFS for commercial plant overseas	**Tianqi (WA)** $LiHO_2$ plant, not yet operational
Nickel- and cobalt-sulphate		**BHP NickelWest** Produces cobalt-nickel sulphide precipitate, pilot nickel sulphate plant **CleanTeQ** HPAL and CleaniX extraction, pilot and DFS complete **PureMinerals/QPM** Battery grade nickel from MHP using Direct Nickel Process. Further refinement into nickel- and cobalt- sulphate at CSIRO **Pure Battery Technologies** SAL to upgrade MHP to battery grade nickel **Cobalt Blue** Cobalt and cobalt sulphate, pyrolysis and leaching process	
Manganese sulphate	**Element25** High purity manganese sulphate and EMM powered by renewable energy, PFS complete for mining project, pilot testing funded by CRC-P **Pilbara Metals/Mn Energy** High purity manganese sulphate. CRC-P funded development.		

CRC-P: Cooperative Research Centre projects
DFS: Definitive feasibility studies
EMM: Electrolytic manganese metal
HPAL: High pressure acid leaching
MHP: Mixed hydroxide product
PFS: Pre-feasibility studies
SAL: Selective acid leaching

Figure 19: Current state for processing of precursor chemicals for LiNMC cathodes[240]

In the Australian context, successful production of precursor chemicals should then lead to commercial production of P-CAM and CAM. Recent studies commissioned by the Future Battery Industries Cooperative Research Centre (FBICRC) have indicated that local production is likely to be technically and economically feasible.[241] However, one of the primary challenges relates to meeting the required and often bespoke specifications of OEMs which are typically held in complex patents. A proposed solution, which is the focus of the FBICRC and the WA Government (who committed funding in 2020), is to attract an established OEM to co-develop a manufacturing facility that can leverage the BHP Nickel Sulphate pilot plant currently under development.

Cathode (LFP)

As a precursor for LFPs, phosphate rock is beneficiated to improve the concentration of phosphorus pentoxide and then processed into phosphate compounds such as phosphoric acid or ammonium phosphate. This is somewhat consistent with upstream processing for a series of fertilisers, namely phosphoric acid and monoammonium phosphate.

Notably, Incitec Pivot operates Australia's sole integrated mine and fertiliser grade phosphoric acid and monoammonium phosphate production plant in Phosphate Hill (Qld). This plant would require further upgrades to enable production of concentrated purified phosphoric acid suitable for LFP batteries. Such upgrades are significantly less capital intensive than greenfield production plants and given the higher volumes of phosphoric acid required, LFP CAM manufacturing is more likely to occur in QLD as opposed to WA where the majority of lithium is mined.[242]

The various LFP CAM production methods are also subject to a series of complex patents with high licensing fees. However, these patents are set to expire in 2022 which increases scope for companies such as VSPC to develop a local LFP CAM manufacturing facility.[243]

240 Best A and Vernon C (2020) State of Play: Australia's Battery Industries as at March 2020. CSIRO, Australia; Information updated 28 January 2021 from respective company websites and ASX announcements.

241 QUT (2020) Li-ion battery cathode manufacture in Australia: A Scene Setting Project. FBICRC, Australia.

242 The ratio of Lithium to Phosphorus in LiFePO4 cathode is roughly 1:5. Li2CO3 contains roughly 19% lithium. H3PO4 contains roughly 32% phosphorus; Richardson A (2020) Fertilizer Manufacturing in Australia. IBISworld. Viewed 20 November 2020, <https://my.ibisworld.com/au/en/industry/c1831/operating-conditions>.

243 Roskill (2020) LFP Cathodes June 2020: White Paper.

Case Study: Lithium Australia/VSPC

VSPC (a subsidiary of Lithium Australia) is focused on producing high purity refined lithium phosphate powder and other metal oxides for cathode materials. They have developed a scalable, low energy and low waste manufacturing process based on fluid chemistry wherein the product can be tailored to various end use applications.[244] Current production is at pilot scale in Brisbane.[245] The company has also partnered with Chinese battery producer, DLG Battery Co. Ltd, with the intention of supplying VSPC patented cathode powders for battery manufacture.[246]

Anode (Graphite)

Following extraction, natural graphite goes through a process of crushing and floatation to produce a 95% graphite concentrate. The graphite is then 'spheronised' to achieve spherical particles. This is followed by heating and chemical treatment to achieve battery grade purity (i.e. 99.97%).[245] The graphite is then coated and combined with small amounts of silicon to produce battery anodes.

As shown in Table 4, Australia is developing a series of capabilities relating to battery anode material production. However, as mentioned in Part I, a lack of existing mining operations and uncertainty over the potential for Australian resources has meant that the opportunity to derive value-add opportunities from domestic natural graphite deposits remains somewhat unclear.

Lastly, although current demand for silicon in anodes is minimal and unlikely to drive development of HPQ, it does represent another potential offtake, particularly if technical barriers to increased silicon content in anodes are overcome (discussed in Section 2.2 Part I and Appendix B).

High Purity Alumina (HPA)

HPA is a high-grade (99.99% or above) form of alumina that can be used as a ceramic coating for separators in LiBs to improve thermal stability.[248] Whereas alumina is conventionally produced from bauxite and then converted to aluminium (explained further in Appendix B), the HPA market typically uses aluminium as a feedstock (or other refined aluminium compounds) and chemically converts it back to alumina.[249]

The market for HPA is expected to grow by nearly 21% each year to 2026.[250] Further, given that it is an expensive process (due to the cost of aluminium feedstock and electricity),[249] a number of Australia companies (included in Table 5) are developing novel processes to enter the HPA market. This includes aluminium processing via leaching (with a comparatively reduced cost and environmental footprint), kaolin clay mining and processing (usually via hydrochloric acid leaching) and use of HPA as a co-product of LiNMC precursor chemicals production (from mixed hydroxide precipitate). These have reached varying stages of development but are yet to reach commercial scale production.

Table 4: Graphite anode value chain steps and current Australian activity

Step	Current State[245]
(Natural) Graphite extraction	Feasibility studies e.g. Mineral Commodities Ltd in Munglinup (WA) and Renascor Siviour mine in Eyre Peninsula (SA).
Spheronised, purified	Prospective manufacturing facilities by companies such as EcoGraf using imported natural graphite from Tanzania. Renascor validation study completed, purified spherical graphite from the Siviour graphite site meets product specifications for producing anode material.[247]
Spheronised, coated	Prospective manufacturing facilities by companies such as Archer Materials Ltd, sourcing graphite from a deposit in SA.
Silicon addition	Anteo and Sicona are developing composite materials to increase silicon content to be integrated in the matrix of the anode material (overcoming expansion issues) in order to increase storage capacity, cost effectiveness, weight, and size of batteries.

244 Lithium Australia (2020) VSPC. Viewed 12 November 2020, <https://lithium-au.com/vspc/>.

245 Best A and Vernon C (2020) State of Play: Australia's Battery Industries as at March 2020. CSIRO, Australia.

246 Lithium Australia (2019) Lithium Australian Forms alliance with leading Chinese battery producer. Viewed 4 January 2021, <https://lithium-au.com/wp-content/uploads/2016/11/09052019-LIT-forms-alliance-with-leading-Chinese-battery-producer-1.pdf>.

247 Renascor Resources (2020) ASX Release, Siviour Purified Graphite Meets Anode Manufacturer Specifications. Viewed 11 February 2021, <https://renascor.com.au/wp-content/uploads/2020/08/20200812-Siviour-Spherical-Graphite-Meets-Anode-Specifications-2096748.pdf>.

248 It should be noted that other separator types exist as a substitute technology, namely composite membranes; Altech Chemical Limited (2020) High Purity Alumina (HPA) Application on Lithium Ion Battery Separator. White Paper, May 2020.

249 Altech Chemicals (2020) The Global High Purity Alumina Market. White Paper, March 2020.

250 Chaudhary A et al. (2020) High Purity Alumina Market Outlook – 2026. Allied Market Research, US.

Table 5: Emerging Australian HPA producers

Project type	Company	
HPA from aluminium via leaching[251]	Alpha HPA (NSW)	
HPA from kaolin clay[252]	Lavablue (Qld) Altech (WA mine, Malaysia processing) FYI Resources (WA)	Andromeda Metals (SA, export to China for processing) Alchemy Resources (NSW)
HPA co-product from LiNMC precursor chemicals[253]	PureMinerals (Qld)	

5.1.2 Manufacturing

LiB manufacture involves the production of cells followed by assembly of the battery pack and management systems.

With respect to stationary storage, there are several trends that could lead to domestic manufacture of batteries. This includes local demand that stems from the continued roll out and pairing with distributed renewable energy systems for residential, commercial and industrial applications (i.e. ~200 GWh of cumulative installed capacity in Australia to 2050). This may be furthered via the development of battery systems that are unique to the Australian climate, a current focus of emerging Australian OEMs such as Energy Renaissance (discussed further below).

A more challenging scenario arises in relation to battery systems for EVs given that OEMs tend to locate their facilities adjacent to mass vehicle production (primarily in Europe and Asia). Given that 40% of an EV's value is in the battery, leading manufacturing nations are competing to consolidate supply chains within their respective jurisdictions.[254] Australia's relatively low population, modest automotive industry and distance from major markets also makes large scale battery manufacture for EVs less attractive. However, there may still be niche markets within the EV sector that represent opportunities for local battery and EV manufacture (refer to ACE-EV example in Section 1.2).

Australia's comparative strengths, relating to the battery cell, pack and management systems are detailed below.

Cell production

Cell production involves the integration of the cathode and anode, separator, cell enclosure material, electrolyte and aluminium and copper foils. As none of these materials are currently manufactured in Australia, deployment of cell manufacturing facilities would likely rely on imported components in the near term in order to de-risk the initial investment.[255] This is the approach being taken by Energy Renaissance who subsequently intend to shift towards greater use of local materials. It is important to note that successful scale up could lead to greater investor confidence in similar battery ventures within Australia in the coming years.

Case Study: Energy Renaissance[256]

Energy Renaissance is seeking to manufacture LiBs optimised for hot climates (Australia and South East Asia). Its initial product line will be industrial grid batteries, and eventual expansion into batteries for special purpose vehicles. The company recently announced Australia's first gigawatt scale LiB factory in NSW and plans to scale this to 5.3 GWh a year in the next decade. To develop these battery systems, Energy Renaissance is licencing its core cell technology from Cadenza Innovation (US) and combining this with an electrode chemistry agnostic battery pack. The company is seeking to reduce the cost of energy by establishing its facility in Newcastle where it can leverage the region's high solar potential, skilled labour pool from other industries and existing port infrastructure. The company also aims to be utilising 100% locally sourced materials within 3 years on the basis that an integrated value chain will become more commercially and strategically viable in the future. Comprehensive automation of production lines is also expected improve project economics.

251 AlphaHPA (2021) HPA First. Viewed 1 February 2021 <https://www.alphahpa.com.au/index.cfm/our-projects/hpa-first/>

252 Lava Blue (2021) High Purity Alumina Al2O3. Viewed 1 February 2021 <https://www.lavablue.com.au/hpa>; Altech (2021) High Purity Alumina (HPA) Project. Viewed 1 February 2021 <https://www.altechchemicals.com/high-purity-alumina-hpa-project>; FYI Resources (2019) Pilot Plant Overview. Viewed 11 January 2021, <https://www.fyiresources.com.au/media/files/FYI-Presentation-September-2019-Pilot-Plant.pdf>; Andromeda Metals (2019) ASX Announcement, 28 May 2019. Viewed 11 February 2021, <https://www.andromet.com.au/images/uploads/reports/20190528_CMP_China_visit_to_Poochera_FINAL.pdf>; Alchemy Resources (2021) West Lynn and Woodsreef Projects (NSW). Viewed 1 February 2021, <http://alchemyresources.com.au/cobar-basin-lachlan-fold-belt-projects-nsw-2/>.

253 Pure Minerals (2021) TECH Project. Viewed 29 January 2021, <https://www.pureminerals.com.au/projects/tech-project-2/>.

254 Benchmark Mineral Intelligence (2017) Lithium ion batteries are now selling for under $140/KWH. Viewed 15 January 2021, <https://www.benchmarkminerals.com/lithium-ion-batteries-are-now-selling-for-under-140kwh-new-york-hears-on-benchmark-world-tour-2017/>; European Commission (2019) Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank on the Implementation of the Strategic Action Plan on Batteries: Building a Strategic Battery Value Chain in Europe. Brussels, 2019

255 ATIC (2018) The Lithium-Ion Battery Value Chain: New Economy Opportunities for Australia.

256 Vorrath S (2020) Energy Renaissance names Hunter region for Australia's first battery "gigafactory". Renew Economy. Viewed 22 November 2020, <https://reneweconomy.com.au/energy-renaissance-names-hunter-region-for-australias-first-battery-gigafactory-66924/>; PV Magazine (2020) Energy Renaissance lithium-ion Gigafactory breaks ground in Tomago NSW.

Similar to CAM manufacturing, with significant investment in mature LiB cells (i.e. LiNMC and LFP) having taken place for decades offshore, Australian cell manufacturing capacity is likely to continue to be stifled by complex patents and licencing fees for core IP. Thus, while investment in mature LiB systems is needed to stimulate domestic supply chains, it is important to balance this with a longer-term view of the sector to ensure the continued viability of battery manufacture in Australia. This includes the pursuit of new component materials, additives and coatings to improve the performance of complex and emerging chemistries.[257]

Importantly, Australia has previously demonstrated the ability to further develop new materials for existing batteries with the commercialisation of CSIRO's Ultra-Battery. This involved the integration of an advanced part carbon and lead electrode into established lead-acid batteries that have been successfully commercialised in the US and Japan. The longstanding challenge however is to ensure that manufacturing remains onshore.

Battery pack and battery management systems

Production of battery packs involves connecting individual cells and battery management systems (BMS) to ensure the battery can operate safely and optimally. Although not a significant value-add component, BMS are becoming increasingly important in improving the overall performance of LiBs, particularly as the industry moves towards more powerful and complex battery chemistries.[258]

Australia has demonstrated capabilities in novel BMS that can provide significant improvements in battery performance. For instance, Relectrify have developed BMS and inverter technology that unlocks the capacity of individual cells in the pack and is particularly useful for battery repurposing (i.e. 'second life') applications. This eliminates additional inverter costs, minimises cell capacity losses, enhances safety and increases pack life.[259] The company recently piloted its technology with American Electric Power and Nissan North America.[259]

5.1.3 Recycling

LiB recycling represents an important economic opportunity due to the expected value of the underlying materials. For instance, approximately 35,000 t of cobalt, 86,000 t of nickel and 125,000 t of lithium carbonate equivalent could be recovered by 2030, representing a $6 billion opportunity globally.[260] This also enables greater control over the flow of critical minerals and reduces environmental impact.[261]

To date, closed-loop LiB recycling in Australia has been limited. Several companies manage battery waste but export it as an unseparated end product to Asia for further processing.[262] Envirostream is the only company with integrated collection, sorting and separation activities, with the resulting mixed metal dust product exported to Korea.[263]

Domestic standards are also relatively undeveloped. For instance, national guidelines were recently (2020) published by the Australian Battery Recycling Initiative and the Battery Stewardship Council (BSC) has been authorised to establish a voluntary national scheme for launch in 2021.[264] LiBs are also currently being considered for inclusion in the Product Stewardship Act.[265]

For Australia to play a key role in the emerging battery recycling market, there are a number of barriers to overcome. Firstly, as a comparatively small market, it is unclear whether the volumes and variability in battery waste streams will be sufficient to achieve the requisite economies of scale to ensure the economic viability of a given recycling plant.[266] While there is potential for Australia to import batteries from markets within a reasonable proximity, issues relating to transport costs and associated fire risks must be addressed.[266]

257 Roskill (2020) Lithium-ion Batteries: Outlook to 2029, 4th Edition.

258 Best A and Vernon C (2020) State of Play: Australia's Battery Industries as at March 2020. CSIRO, Australia; Ouyang D et al. (2019) A Review on the Thermal Hazards of the Lithium-Ion Battery and the Corresponding Countermeasures. Applied Sciences. DOI: 10.3390/app9122483.

259 Relectrify (2020) Relectrify BMS+Inverter. Viewed 19 November 2020, <https://www.relectrify.com/technology>.

260 Jamasmie C (2019) Recycled lithium batteries market to hit $6 billion by 2030 – report. Viewed 19 October 2020, <https://www.mining.com/recycled-lithium-batteries-market-to-hit-6-billion-by-2030-report/>.

261 Beaudet A et al. (2020) Key Challenges and Opportunities for Recycling Electric Vehicle Battery Materials. Sustainability. DOI: 10.3390/su12145837.

262 Ecocycle (2020) Battery Recycling: HEV, PHEV, EV and E-Bike Batteries. Viewed 19 October 2020, <https://ecocycle.com.au/battery-waste-recycling-recovery/battery-recycling-hev-phev-ev-e-bike-batteries/>; MRI e-cycle solutions (2020) Battery Recycling. Viewed 19 October 2020, <https://mri.com.au/services/e-waste-and-battery-recycling/battery-recycling/>.

263 Envirostream (2020) Processing. Viewed 19 October 2020, <https://envirostream.com.au/processing/>; TechInvest (2019) Major breakthrough for Lithium Australia with signing of Korean LiB MOU. Viewed 19 October 2020, <https://techinvest.online/major-breakthrough-for-lithium-australia-with-signing-of-korean-lib-mou/>; Waste Management Review (2019) LG chem partners with Envirostream. Waste management Review. Viewed 19 October 2020, <https://wastemanagementreview.com.au/lg-chem-partners-with-envirostream/>.

264 Envirostream (2020) Recycling Batteries Guideline: Packaging and safe transport of mixed batteries. Australia Battery Recycling Initiative, Australia.

265 ACCC (2020) Voluntary battery stewardship scheme granted authorisation. Viewed 21 October 2020, <https://www.accc.gov.au/media-release/voluntary-battery-stewardship-scheme-granted-authorisation>; BSC (2019) Proposed Stewardship Scheme for Batteries. Battery Stewardship Council, Australia; Department of Agriculture, Water and the Environment (2020) 2020–21 Product List. Viewed 21 October 2020, <https://www.environment.gov.au/protection/waste-resource-recovery/product-stewardship/legislation/product-list-2020-21>.

266 King S et al. (2018) Lithium battery recycling in Australia: Current status and opportunities for developing a new industry. CSIRO, Australia.

Additionally, global shipping regulations for batteries would also need to be standardised given current variability across jurisdictions and modes of transport.[267]

Secondly, the variety of LiB battery chemistries and contaminants make it difficult to configure and plan for recycling infrastructure for the long term. Further, there is currently a lack of transparency regarding battery content, largely due to protection of IP, and no industry standards exist requiring adequate disclosure and labelling.

Thirdly, improvements in processing technology are still required to achieve high product grades for battery re-manufacture. This includes reducing the levels of electrical and thermal energy required and managing waste by-products and emissions generated from the recycling process.[268] For this reason, the industry is shifting from pyrometallurgical towards hydrometallurgical processing which achieves higher materials recovery and quality, is less energy intensive, flexible to any battery chemistry and can achieve more targeted end products.[268]

In the immediate term, there may also be an opportunity to derive additional value by recycling battery electrolyte. $LiPF_6$ electrolyte can be recovered to a high degree of purity and be directly re-used.[269]

5.2 Value chain opportunities – Vanadium redox flow batteries

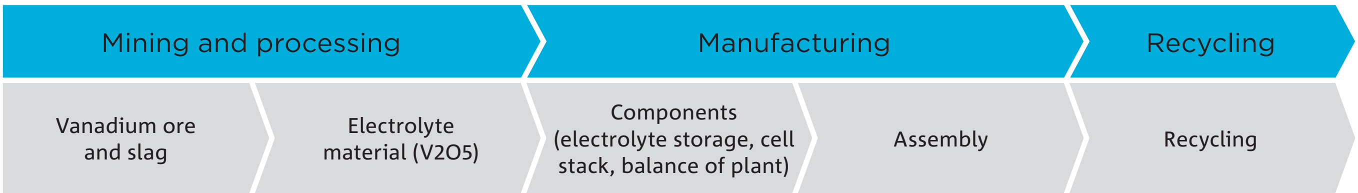

Figure 20: Vanadium redox flow battery value chain

5.2.1 Critical minerals mining and processing

As mentioned in Section 2.2 Part I, the viability of a vanadium industry in Australia will likely depend on the steel alloy market. If successful however, there is significant opportunity to develop materials needed to support the vanadium redox flow batteries (VRFB) value chain.

High purity vanadium pentoxide (V_2O_5) electrolyte acts as both the anode and cathode. While processing pathways from ore to final product depend on the composition of the feedstock, vanadium ore or slag is generally turned into an aqueous solution and treated to remove various impurities before being processed into V_2O_5.[270] The electrolyte is then produced by dissolving the V_2O_5 in sulphuric acid. Although less commonly cited, other vanadium compounds can be used for the preparation of electrolyte including vanadyl sulphate ($VOSO_4$) and vanadium trioxide (V_2O_3).[271]

The V_2O_5 method is currently being pursued by Australian Vanadium. Should they be successful in developing their vanadium resource, the company is likely to divert part of this supply for electrolyte production. Australian Vanadium recently demonstrated its process using feedstock obtained from the US, achieving high purity V_2O_5 (99.4%) via a traditional leaching and hydrometallurgical pathway.[272]

5.2.2 Manufacturing

There are several components in the manufacture of VRFBs including the cell stack, electrolyte storage, and balance of plant. Given the relative nascency and more niche application, local activity in Australia has been limited to installations using imported equipment. For instance, VSUN (an Australian Vanadium subsidiary) achieved its first installation in Busselton (WA) utilising a CellCube system from Austria.[273] The same supplier is expected to be used

267 See UN Model Regulations, IATA DGR (International Air Transport Association Dangerous Goods Regulations), ICAO (International Civil Aviation Organization), IMDG (International Maritime Dangerous Goods) Code, European ADR (Agreement concerning International Carriage of Dangerous Goods by Road) and RID (Regulation concerning the International Carriage of Dangerous Goods by Rail).

268 Beaudet A et al. (2020) Key Challenges and Opportunities for Recycling Electric Vehicle Battery Materials. Sustainability. DOI: 10.3390/su12145837.

269 Kirkpatrick M (2020) The waste problem hiding in your mobile phone. CSIRO ECOS. Viewed 11 February 2021, <https://ecos.csiro.au/the-waste-problem-hiding-in-your-mobile-phone>.

270 Zhang J et al. (2014) A Critical review of Technology for Selective Recovery of Vanadium from Leaching Solution in V2O5 production. Solvent Extraction and Ion Exchange. DOI: 10.1080/07366299.2013.877753; Ma Y et al. (2018) Preparation of Vanadium Oxides from a Vanadium (IV) Strip Liquor Extracted from Vanadium-Bearing Shale Using an Eco-Friendly Method. Metals. DOI: 10.3390/met8120994.

271 Martin J et al. (2020) Preparation of Electrolyte for Vanadium Redox-Flow Batteries Based on Vanadium Pentoxide. Energy Technology. DOI: 10.1002/ente.202000522.

272 TechInvest (2020) Testwork confirms high purity V2O5 product for Australian Vanadium project. Viewed 11 November 2020, <https://techinvest.online/testwork-confirms-high-purity-v2o5-product-for-australian-vanadium-project/>.

273 VSUN Energy (2020) A Renewable Energy Company. Presentation, August 2020.

for Australia's first MW scale plant in Australia which was recently announced by Pangea Energy Pty Ltd.[274]

With major manufacturers in China (also a leading supplier of vanadium) already developing their own local supply chains, potential for Australian manufacture of VRFB components is likely to depend on domestic demand. Notably however and in contrast to LiBs, Australia holds key VRFB IP with the technology first invented at the University of New South Wales in the 1980s. Since then, the university has continued to invest in ongoing improvement of VRFB systems.[275]

5.2.3 Recycling

With some uncertainty regarding projected demand for VRFBs, there is minimal attention being given to the potential for local recycling. Further, the economic viability of VRFB recycling is uncertain due to the absence of high value materials outside of the electrolyte component which makes up 88% of the battery.[276] Given that the electrolyte does not degrade during cycling, VSUN, who is already installing VRFBs in Australia, plans to lease the electrolyte to customers. Other recyclable components include polyvinyl chloride (3%), aluminium (4%) and small volumes of high density polyethylene, rubber and mixed metal.[276]

5.3 Value chain specific investment priorities

5.3.1 Commercial

Streamlining graphite resources

As mentioned in Section 5.1.1, there is currently some conjecture regarding Australia's potential for graphite production. For instance, emerging companies such as EcoGraf are seeking to import natural graphite from Tanzania for processing onshore. Meanwhile, Mineral Commodities Ltd is conducting feasibility assessments at Munglinup (WA) with a view to exporting the product to their processing plant in Norway.

A streamlined approach will therefore be needed to ensure that opportunities associated with mining and downstream processing of graphite can be realised. As a starting point, further exploration and characterisation of local deposits will be needed to provide greater certainty around the quality and quantity of Australian natural graphite resources. Further, given the number of comparatively small deposits (compared to Africa), graphite could provide an important test bed for the implementation of more flexible and modular mining models (discussed in Section 1.1.1). International examples of companies undertaking this for graphite include NextSource Materials (Canada), who is aiming to install modular supply build technology by the end of 2021.[277]

Case Study: NextSource (Canada)

NextSource, a mine development company based in Canada, is collaborating with SYNCS Engineering and Technology to implement one of the first fully modular permanent graphite mines (located in Madagascar).[277] The modular elements include the permanent processing plant, crushers, flotation equipment, concentrate drying, generators, water and sewage treatment, and buildings.[278] The first phase of the plant will produce 17,000 tonnes of concentrate and take 9 months to build. Phase 2 will involve a scale up in production to 45,000 tonnes a year by adding more modules.[277] The company secured a binding offtake in 2018 with a Japanese trading house and also intends to partner with a Chinese OEM to collaborate on battery anode production.[279]

274 Bloomberg (2019) CellCube and Pangea Energy Have Signed LOI for 50MW/200MWh in Australia. Viewed 10 February 2021, <https://www.bloomberg.com/press-releases/2019-05-14/cellcube-and-pangea-energy-have-signed-loi-for-50mw-200mwh-in-australia-jvngik0i>.

275 UNSW (n.d.) Vanadium Redox Flow Battery. Viewed 17 November 2020, <https://www.torch.unsw.edu.au/sites/default/files/Vanadium%20Redox%20Flow%20Battery_EN_0.pdf>.

276 Gouveia J et al. (2020) Life cycle assessment of a vanadium flow battery. Energy Reports. DOI: 10.1016/j.egyr.2019.08.025; Weber S et al. (2018) Life Cycle Assessment of a Vanadium Redox Flow Battery. Environmental Science Technology. DOI: 10.1021/acs.est.8b02073.

277 NextSource Materials (2020) Full Modular Construction. Viewed 4 December 2020, <http://www.nextsourcematerials.com/graphite/molo-graphite-project/modular-approach/>.

278 NextSource Materials (2018) NextSource Materials Inc. Annual Information form (AIF): For the year ended June 30, 2018. Viewed 18 December 2020, <https://fintel.io/doc/sec-nsrc-nextsource-materials-ex3-2018-september-29-18404-515>.

279 Nasdaq (2020) NextSource Materials signs Letter of Intent with Japanese Offtake partner and Prominent Chinese Graphite Anode OEM Supplier to Collaborate on Battery Anode Plant. Viewed 18 December 2020, <https://www.nasdaq.com/press-release/nextsource-materials-signs-letter-of-intent-with-japanese-offtake-partner-and>.

Vertically integrated P-CAM and CAM production

For LiNMC specifically, there is a unique opportunity to vertically integrate mineral extraction through to P-CAM and CAM production in WA. This is due to the proximity of all the required minerals which can reduce overall production costs and improve global competitiveness. CAM production also allows for the export of higher value products given that with the exception of lithium, export of precursor chemicals reduces the embedded value of the metal due to the addition of low value materials such as sulphur and water. Further, localised CAM production encourages further supply chain diversification for global OEMs and increases the potential for further moves downstream in Australia (i.e. cell production).

Battery hubs/clusters

Co-located organisations within innovation 'clusters' or 'hubs' have a greater likelihood of attracting financing, enhancing collaboration and enabling the adoption of new technologies.[280] Finland provides one example of a country focused on development of a battery cluster comprising key local entities across the battery value chain.[281]

The proximity of the required minerals for LiB and VRFB battery systems means that Australia is also well placed to create a local battery cluster. For instance, companies such Tianqi (lithium hydroxide), BHP Nickel West (precursor chemicals), and Ecograf (graphite anode) have pilot or prospective processing operations in Kwinana which already serves as an industrial hub.

Building on current activities, there is also an opportunity to accelerate ongoing efforts to establish battery 'Centres of Excellence' in the region which can help overcome some of the barriers to developing downstream processing. For instance, by including testing facilities, these centres can reduce the time and cost associated with meeting OEM specifications and can provide a more attractive proposition for companies looking to deploy new manufacturing facilities. As many battery components are currently being developed by different suppliers in isolation, these facilities are also needed to test the integration of components in order to properly assess their performance.[282]

5.3.2 Policy/regulatory

Classification of intermediate products

As discussed in Section 1.1.2, incentivising investment in the production of precursor chemicals and CAM will require existing royalty systems to be revisited. This is largely due to confusion regarding whether production of such intermediates is deemed a mining or a chemical process (i.e. blurring of the mine gate boundary). This is particularly the case where precursors such as manganese sulphate are produced via an integrated process.

WA is an early mover in this context, recently moving to include lithium hydroxide and lithium carbonate royalty rates. The revised scheme places a five per cent feedstock royalty rate on these precursors and is applicable to circumstances where they are the first products sold to another entity.[283]

Recycling

Although recovery of high value materials such as cobalt could see battery recycling become commercially viable in the long term, robust stewardship programs will be required in the near term to ensure efficient materials collection. For instance, continuous improvement and expansion of the proposed BSC Stewardship scheme could ensure greater investment in recycling infrastructure. This includes consideration of mandatory participation, alignment with global standards and co-ordination with international battery manufacturers.

Further, due to the particular battery hazards and complex chemistries, there is also a need for policy, regulation, standards and certifications regarding battery labelling, traceability, safety, transport, discharge and processing.[284]

5.3.3 RD&D

Mining and minerals processing

Advances in mining and processing of key materials are required to improve Australia's competitiveness in the global battery market by reducing both cost and environmental impact. A key area of focus involves minimising and improving the steps required from mineral to precursor. A non-exhaustive list of emerging processes is set out below.

280 CSIRO (2020) Value of Science and Technology. CSIRO, Australia.

281 Ministry of Economic Affairs and Employment (2021) National Battery Strategy 2025, MEAE Sector Reports 2021:6, Helsinki.

282 FBICRC (2020) Manufacturing, testing and deployment. Viewed 8 January 2021, <https://fbicrc.com.au/research/manufacturing-testing-and-deployment/>.

283 DMIRS (2019) Lithium royalty amendments to encourage downstream processing. Viewed 8 January 2021, <http://www.dmp.wa.gov.au/News/Lithium-royalty-amendments-to-25938.aspx?busselect=4>.

284 King S et al. (2018) Lithium battery recycling in Australia: Current status and opportunities for developing a new industry. CSIRO, Australia; Randell P (2016) Waste lithium-ion battery projections. Randell Environmental Consulting. Reported prepared for Department of the Environment.

Lithium

Conventional production of lithium precursor chemicals (lithium-hydroxide and -carbonate) from spodumene is an energy and chemical intensive multistep process that generates significant volumes of waste. The first step, calcination, involves heating spodumene to temperatures of approximately 1000°C.[285] Advances in 'flash calcination technology', including improved plant operability, enhanced recovery from fines (i.e. fine particles formed during initial extraction) and efficient phase conversions (i.e. from spodumene-α to β) are enabling substantial reductions in cost and energy consumption.[286]

The subsequent step known as roasting (sometimes performed as part of the calcination process), can be achieved via three methods: acid roasting using sulphuric acid; the alkaline process (which utilises lime or limestone); and the chloride route (which uses various chlorinating reagents).[287] While efforts are ongoing to reduce the associated energy use, cost and environmental impact, novel ways of bypassing the calcination and roasting process altogether are being developed.

For example, Lithium Australia's proprietary hydrometallurgical process, SiLeach, uses a combination of sulphuric acid and halide salts to process spodumene without the requirement for roasting to unlock lower grade feedstocks.[288] Similarly, hydrofluoric acid mixed with sulphuric acid has also shown promise as an alternative to calcination of spodumene given it results in a more reactive product amenable for subsequent processing.[289]

Further, closed-loop leaching using nitric acid is an early stage alternative that can also help avoid the roasting process to yield pure lithium nitrate. This can then be then be converted into lithium oxide, an ideal precursor for both lithium chemicals and lithium metal.[290] Potential benefits of this method include reduced cost, safer reagents and recyclability of nitric acid.

Nickel and cobalt

Whereas conventional hydrometallurgical processes for recovery of nickel and cobalt from laterite ores involve high-pressure acid leaching with sulphuric acid, the direct nickel process instead uses nitric acid to achieve a similar nickel recovery rate (i.e. 95%) with a reduced emissions intensity.[291] Queensland Pacific Minerals is one company currently undertaking a pilot scale demonstration of this process.[292]

Another emerging process developed by Pure Battery Chemicals (a spinoff company from the University of Queensland) uses selective acid leaching (SAL) to upgrade mixed hydroxide precipitate into nickel and cobalt precursors. This process is more flexible, cheaper and more environmentally friendly than conventional hydrometallurgical processes.[293] Similarly, Mining & Process Solutions based in WA is developing an environmentally benign hydrometallurgical process known as 'Glyleach' which relies on the use glycine (an amino acid) as the reagent.[294]

Manganese

Currently, manganese metal is produced primarily via pyrometallurgical, hydrometallurgical or electrolytic processes. The growing demand for high purity manganese metal (EMM) and electrolytic manganese dioxide (EMD) has furthered interest in processing technologies with reduced capital expenditure and lower energy requirements.[295] Examples include improved electrodeposition techniques and use of different reducing and leaching agents (e.g. hydrogen peroxide with sulphuric acid).[296] Element 25, in collaboration with CSIRO, is piloting a process that avoids use of sulphuric acid and enables leaching to occur at atmospheric conditions.[297]

285 Abdullah, A et al, 2019, Phase Transformation Mechanism of Spodumene during its calcination. doi.org/10.1016/j.mineng.2019.105883.

286 FBICRC (2020) FBICRC Project Summaries, April 2020.

287 Fosu et al. (2020) Literature Review and Thermodynamic Modelling of Roasting Processes for Lithium Extraction from Spodumene. Metals. DOI: 10.3390/met10101312.

288 Lithium Australia (2020) About SiLeach. Viewed 7 December 2020 <https://lithium-au.com/about-sileach/>.

289 Guo H et al. (2019) Kinetics of leaching lithium from α-spodumene in enhanced acid treatment using HF/H2SO4 as medium. Transactions of Nonferrous Metals Society of China. DOI: 10.1016/S1003-6326(19)64950-2.

290 Hunwick RJ et al. (n.d.) A new 'Closed' process for lithium chemicals production from spodumene and other lithium-silicate minerals. Viewed 7 December 2020, <https://az659834.vo.msecnd.net/eventsairseasiaprod/production-ausimm-public/7919eaa9fc1a4410a21d67b26f19889a>.; Richard Hunwick (2016) Recovery of lithium from silicate minerals. WO2017106925A1, WIPO <https://patents.google.com/patent/WO2017106925A1/en>.

291 Khoo JZ et al. (2017) A life cycle assessment of a new laterite processing technology. Journal of Cleaner Production. DOI: 10.1016/j.jclepro.2016.11.111.

292 Pure Minerals Limited (2020) TECH Project Update. Viewed 15 January 2021, <https://www.asx.com.au/asxpdf/20200916/pdf/44mnx1808cjjlt.pdf>.

293 Pure Battery Technologies (2020) Our Technology. Viewed 4 December 2020, <https://purebatterytech.com/our-technology/>.

294 Mining & Process Solutions (2021) The GlyLeach Process. Viewed 2 February 2021, <https://www.mpsinnovation.com.au/technology/>.

295 Renascor Resources (2020) ASX Release, Siviour Purified Graphite Meets Anode Manufacturer Specifications. Viewed 11 February 2021, <https://renascor.com.au/wp-content/uploads/2020/08/20200812-Siviour-Spherical-Graphite-Meets-Anode-Specifications-2096748.pdf>.

296 Tsurtsumia G et al. (2019) Novel hydro-electrometallurgical technology for simultaneous production of manganese metal, electrolytic manganese dioxide, and manganese sulfate monohydrate. Hydrometallurgy. DOI: 10.1016/j.hydromet.2019.04.028.

297 Brown J (2019) Developing the Butcherbird high purity manganese project. DOI: 10.1080/22020586.2019.12073238; Element 25 (2018) Element 25 Limited Investor Update, May 2018. Viewed 11 January 2021, <https://www.asx.com.au/asxpdf/20180516/pdf/43v1z5w8hhcq78.pdf>.

Cell manufacture capabilities

As mentioned, a focus on continuous and step change improvements in batteries will be important in ensuring the long-term viability of manufacture in Australia by reducing dependence on global OEMs. To advance this, investment in battery RD&D should be tied to Australia's comparative advantage where possible. For example, Australia's lithium resources and leading processing technologies can support future lithium metal anode production required for next generation LiBs. This includes emerging processes such as LithSonic.

Case Study: LithSonic™

Next generation lithium-metal anode batteries (e.g. lithium-sulphur and lithium-air) will require large amounts of lithium metal. However current electrolytic lithium metal production processes generate chlorine emissions.[298] LithSonic™ (derived from CSIRO's MagSonic™ process), overcomes this issue via a novel carbothermal reduction process that produces lithium metal via supersonic quenching of lithium vapor.[299] Although still in the early stages of development, the process is expected to have a lower cost and reduced environmental footprint.

Several Australian entities are currently undertaking work in next generation batteries. They include a wide range of universities,[300] CSIRO and industry-research collaborations such as the Battery Technologies Research and Innovation Hub.[301] Primary research areas include lithium-sulphur, lithium-air, sodium-ion, potassium, calcium, manganese batteries and solid-state electrolytes.[301] Although unlikely to match other jurisdictions in research spend, strategic investment is needed to increase competitiveness with battery powerhouses such as the Europe Battery 2030+ initiative.[302]

Recycling

As discussed in Section 5.1.3, hydrometallurgical processing presents the most promising route for efficient materials recovery. As such, R&D is required to address current challenges relating to cost and effluent management. Further, with much of the focus given to processing Lithium-cobalt-oxide batteries (LCO) and LiNMC batteries to date, more research is needed in relation to other key chemistries such as LFP.[303]

Similarly, despite accounting for 40% of battery content, there has been little attention given to recycling of graphite anodes which typically end up in processing residues.[304] While most graphite research to date has focused on hydrometallurgical and thermal purification methods, further work is needed to overcome the associated toxic waste and energy intensity of these processes.[305] Further, with respect to electrolytes, a key focus is direct extraction and reuse in new batteries, creating an opportunity for value recovery without the requirement for further processing.[306]

To improve recycling, R&D is also needed in pre-processing areas. This includes lifecycle modelling, battery collection, sorting and classification, discharge and pre-treatment, and product design for reuse and recycling.[307]

Lastly, given that batteries retain 75–80% of their capacity at end-of-life, there is also a need to develop designs suitable for repair and re-use. Examples include designs for refurbishment (enabling individual cell replacement rather than decommissioning the entire pack) and battery cell rejuvenation to extend battery life.[308] Other challenges relating to second-life include differences in battery products and a lack of standards and regulations.[308] As such, R&D also should cover the economic and environmental aspects of second-life applications to find optimal solutions.[309]

298 Jewell D et al. (n.d.) LithSonicTM: Powering the next battery revolution. <http://www.imlb2018.org/pdf/a11_2553885.pdf>.

299 CSIRO (2020) LithSonic lithium metal production. Viewed 18 December 2020, <https://www.csiro.au/en/Do-business/Commercialisation/Marketplace/LithSonic-lithium-metal-production>; Prentice LH et al. (2012) Carbothermal Production of Magnesium: CSIRO's MagSonicTM Process. Magnesium Technology. DOI: 10.1007/978-3-319-48203-3_6.

300 Universities with innovation capability include James Cook University, UQ, QUT, UNSW, University of Sydney, UTS, University of Wollongong, Deakin University, Monash University, Swinburne University, University of Melbourne, RMIT, University of Adelaide, University of South Australia, Murdoch University, UWA, Curtin University.

301 Best A and Vernon C (2020) State of Play: Australia's Battery Industries as at March 2020. CSIRO, Australia.

302 BATTERY 2030+ (2020) Research Projects. Viewed 18 December 2020, <https://battery2030.eu/research/research-projects/>.

303 Melin HE (2019) State-of-the-art in reuse and recycling of lithium-ion batteries – A research review. The Swedish Energy Agency, Sweden.

304 Gao Y et al. (2020) Graphite Recycling from the Spent Lithium-Ion Batteries by Sulphuric Acid Curing-Leaching Combined with High-Temperature Calcination. ACS Sustainable Chemistry and Engineering. DOI: 10.1021/acssuschemeng.0c02321.

305 Specifically, hydrochloric acid from HCl leaching, energy intensity of graphitization furnace, and Cl2 waste from converting metals and oxides to chlorides method; Gao Y et al. (2020) Graphite Recycling from the Spent Lithium-Ion Batteries by Sulphuric Acid Curing-Leaching Combined with High-Temperature Calcination. ACS Sustainable Chemistry and Engineering. DOI: 10.1021/acssuschemeng.0c02321.

306 Kirkpatrick M (2020) The waste problem hiding in your mobile phone. CSIRO. Viewed 15 January 2021, <https://ecos.csiro.au/the-waste-problem-hiding-in-your-mobile-phone/>.

307 King S et al. (2018) Lithium battery recycling in Australia: Current status and opportunities for developing a new industry. CSIRO, Australia; Melin HE (2019) State-of-the-art in reuse and recycling of lithium-ion batteries – A research review. The Swedish Energy Agency, Sweden.

308 King S et al. (2018) Lithium battery recycling in Australia: Current status and opportunities for developing a new industry. CSIRO, Australia.

309 Melin HE (2019) State-of-the-art in reuse and recycling of lithium-ion batteries – A research review. The Swedish Energy Agency, Sweden; Hall D and Lutsey N (2018) Effects of Battery Manufacturing on Electric Vehicle Life-cycle Greenhouse Gas Emissions. Briefing, International council on Clean Transportation 2018.

6 Hydrogen

6.1 Value chain opportunities

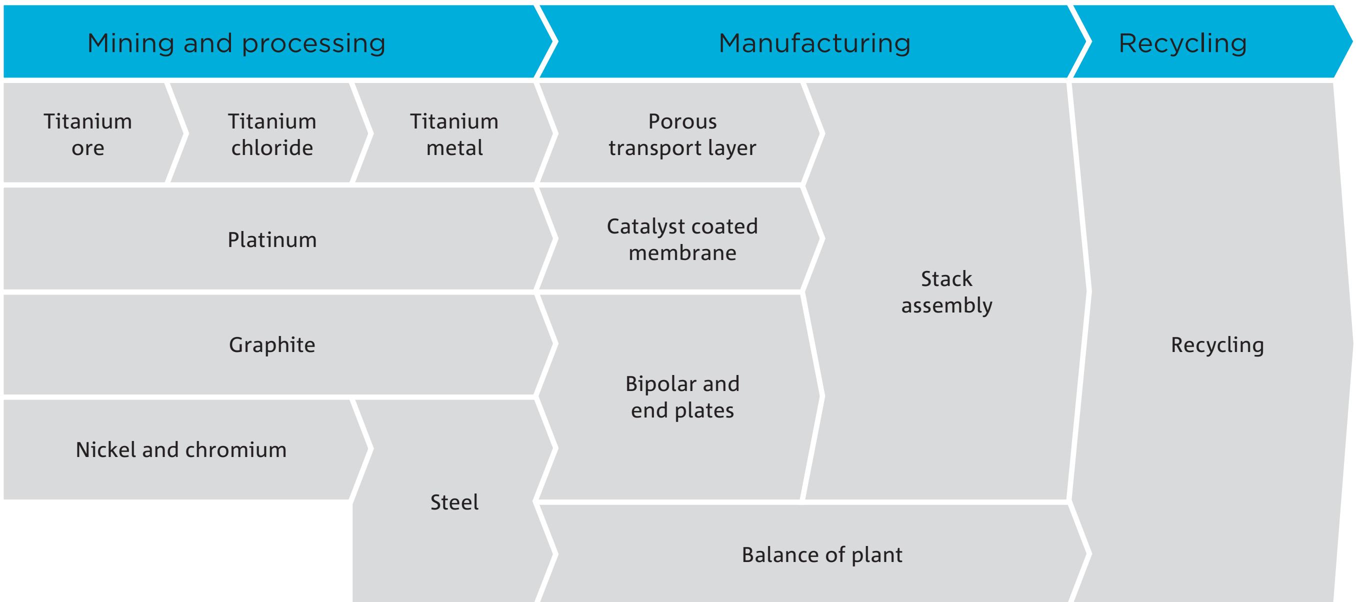

Figure 21: PEM fuel cell and electrolyser value chain

6.1.1 Critical minerals mining and processing

Proton Exchange Membrane (PEM) fuel cells

Platinum is the primary critical mineral in PEM fuel cells. As mentioned in Section 2.2 Part I, although not a dominant producer of Platinum Group Elements (PGEs), there is some potential to develop local deposits.

A number of discrete processing steps are required to first extract base metals, separate PGEs and produce platinum concentrate.[310] This process is capital, energy and chemical intensive given that all of the six PGEs require independent solvent extraction and significant time for leaching.[310] Vertical integration of mining to concentrate production is therefore a common approach assumed by the four major PGE mining companies which together comprise 80% of the market.[310] This places significant barriers to entry on Australian proponents.

Catalyst production is then undertaken through nanoscale processing of high purity platinum metal to maximise surface area.[311] Production is also capital intensive as it requires concentration via flotation, followed by quality controlled particle size processing.[310] As platinum catalysts significantly impact fuel cell performance, downstream manufacturers place strict requirements on purity and structure, and establishment of local production would likely require partnering with an international OEM.[310]

The bipolar plate, which is responsible for converting chemical energy to electricity, is another integral component of PEM fuel cells. While typically made of stainless steel (chromium and nickel alloys) and a metallic coating, there is an increasing move towards substitution with titanium due to its improved electrical conductivity.[312] Titanium processing is discussed below.

310 Sinisalo P et al. (2018) Refining Approaches in the Platinum Group Metal Processing Value Chain – A Review. Metals. DOI: 10.3390/met8040203.

311 Baturina O et al. (2013) Catalytic Processes Using Fuel Cells, Catalytic Batteries, and Hydrogen Storage Materials. S Suib (ed.) New and Future Developments in Catalysis: Batteries, Hydrogen Storage and Fuel Cells. Elsevier, The Netherlands.

312 Asri N et al. (2017) Coating of stainless steel and titanium bipolar plates for anticorrosion in PEMFC: A Review. International Journal of Hydrogen Energy. DOI: 10.1016/j.ijhydene.2016.06.241.

PEM electrolysers

Titanium is used as a porous transport layer within PEM electrolysers to limit the corrosive impact of water.[313] For Australia, there may be an opportunity to divert some existing titanium dioxide production to high purity titanium metal (via the Kroll process). Here, further refining is undertaken by batch processing at high temperatures, with magnesium used as a reductant.[314] This process is capital and labour intensive and it is unlikely that titanium demand from PEM electrolysis alone will be sufficient to justify investment in titanium metal production in Australia.

Notably, prospective rare earth metal producer ASM (discussed in Section 3.1.1) is applying the same electrochemical metallisation process to their titanium resources which could enable a 70% reduction in energy use and allow for continuous processing of titanium metal.[315] This and other emerging titanium metal processes (discussed in Section 6.2.2) could significantly lower the observed barriers to entry and increase the scope for local production.

Similar to fuel cells, PEM electrolysers use platinum as a catalyst which follows the same processing requirements discussed above.

Alkaline electrolysers (AE)

The primary critical metal used in AE is nickel as part of the electrolyser cathode. Given that the volumes of nickel required for electrolysis are likely to be significantly less than batteries, the former could provide an additional demand for nickel but is unlikely to drive local development.

6.1.2 Manufacturing

Given that fuel cell electric vehicle (FCEV) OEMs are primarily located overseas, there is limited opportunity for local manufacture of fuel cells at high volume. However, a different scenario presents in relation to electrolysis where, as a potential exporter of hydrogen and associated fuels, significant local deployment of these systems is likely to be required in Australia.

With respect to the type of electrolyser, AE consists of components currently produced at scale given that they are similar to those used in the manufacture of chlorine and sodium hydroxide (i.e. the Chlori-alkali process).[316] In contrast, PEM electrolysis manufacturing is in its infancy. Given that it also provides an opportunity to create further value from titanium, it is therefore the focus of this section. PEM electrolysis consists of two primary components, the electrolyser stack and balance of plant (BoP).

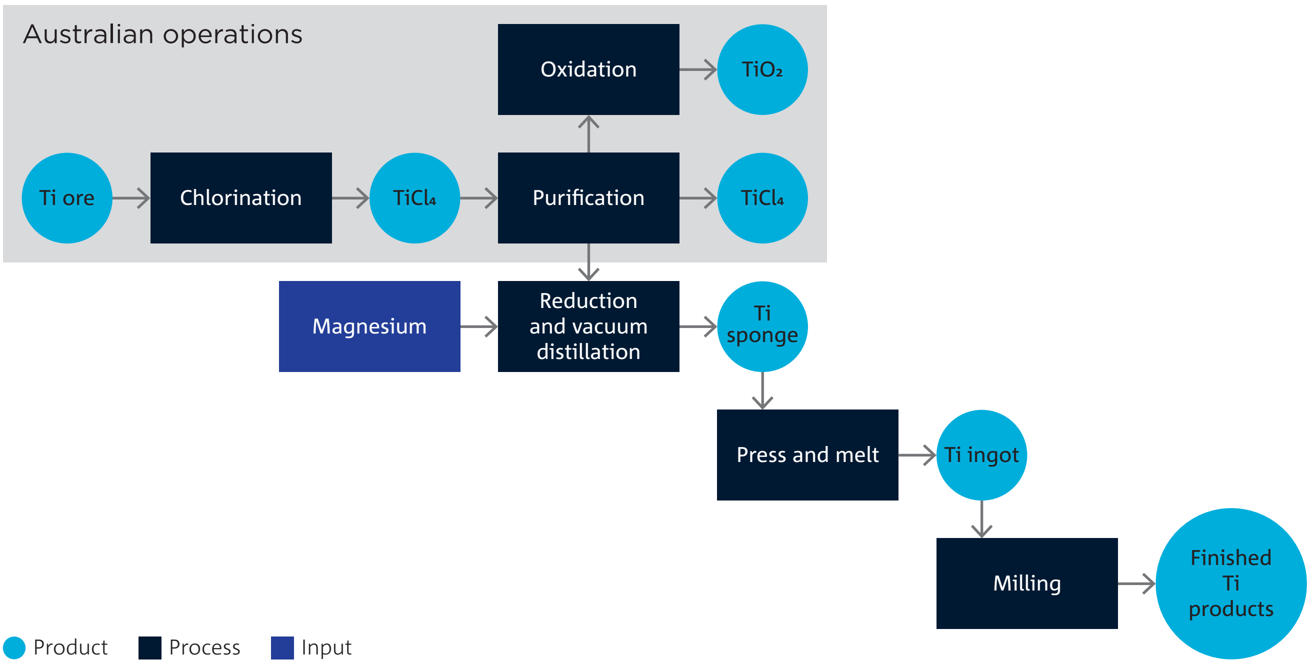

Figure 22: Titanium refining process

313 Kumar S et al. (2019) Hydrogen production by PEM water electrolysis- A review. Materials Science for Energy Technologies. DOI: 10.1016/j.mset.2019.03.002.

314 Seong S et al. (2009) Titanium: Industrial Base, Price Trends, and Technology Initiatives. RAND Corp, USA.

315 ASM (2020) ASM JV produces high purity titanium metal with significant energy and environmental benefits. Viewed 20 December 2020, <https://asmd.irmau.com/site/showdownloaddoc.aspx?AnnounceGuid=819c4269-cd9e-499f-a2a9-36f32f8f6a83>.

316 CSIRO (2018) National Hydrogen Roadmap. CSIRO, Australia.

Stack

The stack is comprised of a number of discrete components, namely the membrane electrode assembly (MEA), bipolar plates as well as the requisite frames and seals. At present, stack component manufacturers, which are concentrated in Europe, supply to both PEM electrolyser and fuel cell OEMs (or stack integrators).[317] However, given that these components are generally not complex to manufacture, most of the stack IP belongs to OEMs due to the impact this has on system performance.[317] Attracting major OEMs onshore is therefore likely to be an important first step in developing local manufacturing capabilities.

Diversification in component supply can be furthered by the need to customise electrolyser design and performance specifically for the Australian climate. This is particularly the case for initiatives such as the Asian Renewables Energy Hub which is expected to require GWs of electrolysis in regions with weather conditions that differ from regions across Europe where major PEM OEMs are currently situated (e.g. high temperatures, dust, cyclones).

Further, although existing PEM electrolysis manufacture has been relatively labour intensive,[318] the expected increase in demand has resulted in OEMs such as ITM Power prioritising the automation of stack production.[319]

Case Study: ITM Power[319]

ITM Power is due to complete phase 1 of its electrolyser factory in 2020 with an estimated output of 300 MW of electrolysers per annum. The factory will be scaled up to achieve an output of 1 GW per annum by 2024. This is being made possible through the semi-automation of stack production for repetitive building of standard products and modules. This semi-automation is expected to reduce capital costs as well as offer precise quality control, efficiency and capacity expansion to other regions.

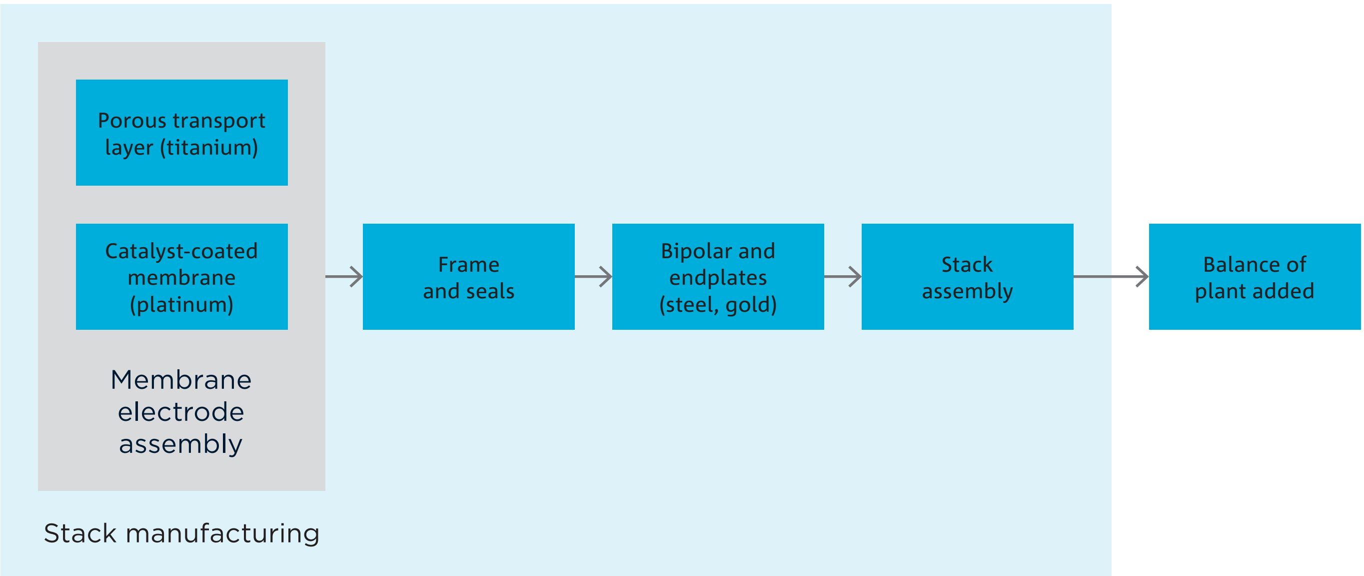

Figure 23: PEM electrolyser manufacturing process

317 E4tech UK Ltd (2019) Study on Value China and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies. FCH 2 JU, UK.

318 Mayyas A et al. (2018) Manufacturing Cost Analysis for Proton Exchange Membrane Water Electrolyzers. NREL, US.

319 ITM Power (2020) Industrial scale renewable hydrogen project advances to next phase. Viewed 10 February 2021, <https://www.itm-power.com/news/industrial-scale-renewable-hydrogen-project-advances-to-next-phase>.

Balance of Plant (BoP)

Electrolyser BoP are responsible for the supply and control of reactants as well as the removal of by-products (e.g. heat). Sensors are also incorporated to monitor and control the flow of reactants, temperature and pressure.[320] The BoP consists of a collection of low complexity components including compressors, heat exchanges, pumps and valves which are standard components that can be easily outsourced to local vendors. Notably, they are heavier and more difficult to transport (compared to system stacks) which also supports local manufacture.

Novel IP

Currently, there are significant R&D efforts dedicated to improving the materials and efficiency of PEM electrolyser systems and consequently the economics of hydrogen production. These step change improvements have the potential to shift manufacturing to regions where the core IP is held, as shown in the case of H_2Pro in Israel.

Case Study: H2Pro[321]

In 2019, leading hydrogen experts from the Israel Institute of Technology founded H_2Pro to develop a hydrogen production technology that is both scalable and environmentally friendly. The electrochemical, thermally activated chemical splitting of water shows improved efficiency, with lower capital expenses due to the absence of a cell membrane. Following the development of this technology, H2Pro formed partnerships with companies across the world, including American company, New Fortress, to support demonstration and commercialisation at industrial scale. Importantly, the company is currently looking for a location to set up its manufacturing facility in Israel.[322]

Such a theme may also materialise for Australia through the continued development of direct ammonia synthesis. This technology uses water and nitrogen as inputs to electrochemically produce ammonia at low temperatures. In doing so, it reduces the process steps from hydrogen to ammonia which minimises operating costs and allows for the production of green ammonia to be coupled with renewable electricity.[323] This will be particularly important in the context of hydrogen export as the global industry explores low-cost high volumetric density carriers for distribution of hydrogen over long distances. This technology is also likely to require the ongoing use of titanium and is currently being pursued by a series of different research institutions (e.g. Monash University) in Australia.

Although not applicable to the export of hydrogen, another current focus within Australia is the development of microelectrolysers. Currently, small scale electrolysers (i.e. 5–40 kW) are not designed specifically for small scale use. Instead, manufacturers will scale down larger units, leading to more costly BoP. Local R&D is therefore focused on design and build of microelectrolysers that best optimise all components of the system.[324] Such developments could make hydrogen affordable at small scale and lead to cost effective distributed solutions for a new range of customers including small communities, commercial and residential buildings.

6.1.3 Recycling

Both fuel cells and electrolyser stacks are expected to have an asset life of approximately 10 years.[325] For FCEVs, this equates to 150,000 kilometres travelled.[326] Thus given hydrogen technologies are in the early stages of rollout, there will be some lead time before sufficient volumes of electrolysers and fuel cells reach the end of their asset life and warrant the need for large-scale recycling plants.

However, the longer term importance of recycling of hydrogen technologies has already been recognised by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) who expect recycling to be achievable by 2030.[327] The FCH JU working group, HyTechCycling, is therefore advancing research and demonstrations for dismantling and recycling these assets.[327] Initial reports suggest that this is likely to

320 Caparros Mancera JJ et al. (2020) An Optimized Balance of Plant for a Medium-Size PEM Electrolyzer: Design, Control and Physical Implementation. Electronics. DOI: 10.3390/electronics9050871.

321 Fuel Cells Works (2020) New Fortress Energy Invest in Green Hydrogen Production technology Company H2Pro. Viewed 17 November 2020, <https://fuelcellsworks.com/news/new-fortress-energy-invests-in-green-hydrogen-production-technology-company-h2pro/>.

322 Manela M (2020) There is a never a bad time to start a venture, says serial entrepreneur. Viewed 7 January 2021, <https://www.calcalistech.com/ctech/articles/0,7340,L-3848939,00.html>.

323 CSIRO (2019) Hydrogen Research, Development and Demonstration: Technical Repository. CSIRO, Australia.

324 ARENA (2019) ATCO Hydrogen Microgrid. Viewed 14 January 2021, <https://arena.gov.au/projects/atco-hydrogen-microgrid/>.

325 Schmidt O et al. (2017) Future cost and performance of water electrolysis: An expert elicitation study. International Journal of Hydrogen Energy. DOI: 10.1016/j.ijhydene.2017.10.045.

326 Benitez A et al. (2020) Ecological assessment of fuel cell electric vehicles with special focus on type IV carbon fiber hydrogen tank. Journal of Cleaner Production. DOI: 10.1016/j.jclepro.2020.123277.

327 HyTechCycling (2019) Roadmap for recycling and dismantling strategies and technologies within FCH technologies. Viewed 7 January 2021, <http://hytechcycling.eu/>.

be economically viable due to the high value of the critical minerals present and component recovery rates of over 80%.[328] However, particularly in relation to fuel cells, many of the same challenges observed in relation to batteries are likely occur, namely the cost of transport to a centralised facility as well as the quantities and configurations used by the various technology providers. That said, in contrast to batteries, there is likely to be less variability between products and negligible quantities of poisonous or hazardous materials.

With this in mind, key fuel cell OEMs such as Ballard have already taken steps to share information about end of life recycling, demonstrating that their products are designed so that no special equipment is needed to dismantle and separate the components.[329] They have also developed a special recycling process for recovering 95% of platinum from the MEA. Thus although the potential to recycle hydrogen technologies is still in its infancy, there is an opportunity for Australia to engage in long term planning for end-of-life processes, particularly with the potential for large-scale centralised manufacturing to support a hydrogen export industry.

6.2 Value chain specific investment priorities

6.2.1 Commercial

Scaling the electrolyser value chain to support hydrogen export

In developing a hydrogen export industry, there are a number of lessons to be leveraged from Australia's Liquefied Natural Gas (LNG) sector. This includes government-to-government agreements which unlock private sector investment, vertically integrated joint ventures, favourable trade tariffs and long term take-or-pay offtake agreements with a flat demand profile.[330]

However, given the expected scale of development, a key risk associated with economically viable hydrogen export relates to ensuring the requisite materials and infrastructure are made available. A failure to do so can increase delays and project costs. Whereas the LNG sector relied primarily on steel and concrete, deployment of PEM electrolysis as a material source of hydrogen production will require a specific focus on the availability of critical minerals, namely titanium. Localising titanium metal supply may therefore be particularly important in de-risking overall industry investment.

6.2.2 RD&D

Titanium metal production

Current titanium metal production (via the Kroll process) involves energy intensive batch processing and results in variable quality as well as increased operating costs.[331] Aside from ASM's electrochemical processing process discussed in Section 6.1.1, there are a number of alternative emerging titanium metal production technologies that support continuous processing.

For instance, CSIRO's TiRO processing technology enables continuous processing using a fluidised bed reactor and a vacuum to directly produce titanium powder.[332] This process offers significant advantages over the traditional Kroll process, as it reduces energy consumption, capital investment and labour costs.[333] In partnership with Australian company Coogee Chemicals, commercialisation of this technology to produce industrial scale titanium alloy powder is underway (2021).[334] Importantly, this process is applicable to manufacture of porous transport layers for PEM electrolysers.[335]

328 Lotrič A et al. (2020) Life-cycle assessment of hydrogen technologies with the focus on EU critical raw materials and end-of-life strategies. International Journal of Hydrogen Energy. DOI: 10.1016/j.ijhydene.2020.06.190.

329 Ballard Power Systems (2017) Recycling PEM Fuel Cells: End-of-life management. Viewed 15 January 2021, <https://www.ballard.com/docs/default-source/web-pdf's/recycling-technical-note_final.pdf>.

330 CSIRO (2018) National Hydrogen Roadmap. CSIRO, Australia.

331 Zhang W et al. (2011) A literature review of titanium metallurgical processes. Hydrometallurgy. DOI: 10.1016/j.hydromet.2011.04.005.

332 Doblin C et al. (2013) The TiRO™ process for the continuous direct production of titanium powder. Key Engineering Materials. DOI: 10.4028/www.scientific.net/KEM.551.37.

333 Whittaker D (2011) Australian Titanium: A new continuous process for the direct production of CP Ti powder developed at CSIRO. Viewed 7 January 2021, <https://www.pm-review.com/articles/australian-titanium-a-new-continuous-process-for-the-direct-production-of-cp-ti-powder-developed-at-csiro/>.

334 Coogee Titanium (2020) Developing and commercialising a revolutionary titanium alloy powder technology. Viewed 7 January 2021, <http://www.coogeetitanium.com.au/>.

335 Schuler T et al. (2019) Hierarchically Structured Porous Transport Layers for Polymer Electrolyte Water Electrolysis. Advanced Energy Materials. DOI: 10.1002/aenm.201903216.

Additive manufacturing

Production of titanium metal is traditionally expensive due to the strength of the metal and consequent wear and tear on capital equipment.[336] Innovative additive manufacturing processes such as tape casting titanium powders may therefore lead to a reduction in costs given the absence of metal machining.[337] Such processes also lead to high precision outputs, complex geometric capabilities and rapid batch processing which can be incorporated in PEM electrolyser manufacture.[338] Australia has a number of key institutions with capabilities that can be leveraged, including RMIT's Advanced Manufacturing Precinct and CSIRO's Lab 22.[339]

Powders and 3D printing

There is potential to manufacture porous transport layers through 'Solvent on Granules 3D-Printing' which uses an ink-jet printer to drop a specialised solvent on granules comprised of titanium hydride powder.[340]

Australia retains strong 3D printing capabilities, particularly with respect to titanium products, that may be leveraged by the hydrogen industry. This includes companies such as Zeal 3D Printing, Titomic and Amaero International.

Alternative catalysts

Given the high cost of platinum, alternative catalysts are currently being explored which have high H_2-conversion efficiency, excellent durability, and operate well under low voltage.[341] Cobalt phosphide nanoparticles is one potential candidate currently being explored for commercial use and is reported to be cheaper than conventional catalysts while achieving similar efficiencies.[342] Further RD&D is required to overcome scalability of the catalyst coating, with peeling (i.e. fragmentation of outer surface) occurring in large-scale applications.[343]

Direct ammonia synthesis

As mentioned, direct ammonia synthesis via electrolysis represents an important opportunity to produce a high volumetric density hydrogen carrier (for export) without the need for conventional Haber-Bosch processing.[344] Although direct ammonia synthesis operates under milder temperatures in a single reactor, the preference of hydrogen ions to bond together (instead of with nitrogen) presents the primary barrier to high ammonia recovery rates.[344] Various electrocatalysts and 'redox mediators' are currently being pursued in order overcome these selectivity challenges.[345]

336 Pramanik A (2013) Problems and solutions in machining of titanium alloys. The International Journal of Advanced Manufacturing Technology. DOI: 10.1007/s00170-013-5326-x.

337 Hackemüller F et al. (2019) Manufacturing of Large-Scale Titanium-Based Porous Transport Layers for Polymer Electrolyte Membrane Electrolysis by Tape Casting. Advanced Engineering Materials. DOI: 10.1002/adem.201801201.

338 Mayyas A and Mann M (2019) Emerging manufacturing technologies for fuel cells and electrolyzers. Procedia Manufacturing. DOI: 10.1016/j.promfg.2019.04.063.

339 CSIRO (2020) Lab22 creates for Australia's manufacturing industry. Viewed 7 January 2021, <https://www.csiro.au/en/Research/MF/Areas/Metals/Lab22>; RMIT (2020) Advanced Manufacturing Precinct. Viewed 7 January 2021, <https://www.rmit.edu.au/about/our-locations-and-facilities/facilities/research-facilities/advanced-manufacturing-precinct>.

340 Carreño-Morelli E et al. (2020) 3D printing of titanium parts from titanium hydride powder by solvent jetting on granule beds. International Journal of Refractory Metals and Hard Materials. DOI: 10.1016/j.ijrmhm.2020.105276.

341 Grad P (2020) A Less Expensive Alternative to Platinum For Water Electrolysis. Chemical Engineering. Viewed 7 January 2021, <https://www.chemengonline.com/a-less-expensive-alternative-to-platinum-for-water-electrolysis-3/>.

342 Zhao X et al. (2020) Cobalt Phosphide-Embedded Reduced Graphene Oxide as a Bifunctional Catalyst for Overall Water Splitting. ACS Omega. DOI: 10.1021/acsomega.9b04143.

343 DGIST (2020) High-Efficiency, Low-Cost Catalyst for Water Electrolysis. Viewed 7 January 2021, <https://phys.org/news/2018-02-high-efficiency-low-cost-catalyst-electrolysis.html>.

344 CSIRO (2018) National Hydrogen Roadmap. CSIRO, Australia.

345 MacFarlane D et al. (2020) A roadmap to the Ammonia Economy. Joule. DOI: 10.1016/j.joule.2020.04.004.

7 EV motors

Permanent magnet generators represent a critical component of EVs given that they improve vehicle torque density and power efficiency without a significant weight penalty.[346] This is enabled by the inclusion of 'electrical steel' which is a soft magnetic steel alloy used to magnetise surrounding components to create a magnetic field in the motor's air gap.[347]

Permanent magnets also represent a material cost component of EV motors which may be impacted by expected growth in EV demand and consequent strain on global REE supply. Some forecasts have suggested that ~40% of global NdPr in 2025 will be required to service this market alone.[348] Heavy REE (e.g. terbium), are also likely to face greater supply constraints in light of EV demand.[349] Alongside the wind sector, EVs therefore represent another important offtake for Australian sourced REEs, particularly heavy REE deposits such as Northern Minerals. Other components of EV motors include the stator, rotor, motor shaft and frame.[350]

As with batteries, high volume manufacturing of EV motors face significant barriers in Australia due to concentration of OEMs overseas and a preference for co-location with auto manufacturing. However, there is potential for Australia to play a role in niche applications, including mining operations where heavy and underground vehicles operate in harsh environments.[351] These niche applications are the focus of Australian company HyperPower Technologies.

Case Study: HyperPower Technologies[352]

HyperPower Technologies (based in WA) is developing high performance EV motors for niche commercial applications, including hyperloop, hypercars and aerospace. The company was spun off from Top EV Racing in an effort to commercialise electric race car motors for other high-performance EVs. Building on over 10 years of research and development, HyperPower has recently begun scaling up assembly and manufacture of their EV motors onshore. HyperPower is also exploring application of their motors to mining applications. Currently all permanent magnets used in HyperPower vehicles are sourced from China.

346 Wang J et al. (2013) Design Optimization of a Surface-Mounted Permanent-Magnet Motor With Concentrated Windings for Electric Vehicle Applications. IEEE Transaction on Vehicular Technology. DOI: 10.1109/TVT.2012.2227867.

347 Rui-Lin P et al. (2012) Studies of High-Efficiency Electrical Steels Used in Electric Vehicle Motors. Journal of Shanghai Jiaotong University. DOI: 10.1007/s12204-012-1277-x.

348 Ballinger B et al. (2020) The vulnerability of electric-vehicle and wind-turbine supply chains to the supply of rare-earth elements in a 2-degree scenario. Sustainable Production and Consumption. DOI: 10.1016/j.spc.2020.02.005.

349 Pavel C et al. (2017) Role of substitution in mitigating the supply pressure of rare earths in electric road transport applications. Sustainable Materials and Technologies. DOI: 10.1016/j.susmat.2017.01.003; Widmer J et al. (2015) Electric vehicle traction motors without rare earth magnets. Sustainable Materials and Technologies. DOI: 10.1016/j.susmat.2015.02.001.

350 IDTechEx (2020) IDTechEx Research: Hot Performance and Coll Operation for Electric Vehicle Motors. Viewed 7 January 2021, <https://www.prnewswire.com/news-releases/idtechex-research-hot-performance-and-cool-operation-for-electric-vehicle-motors-301034456.html>.

351 Adams T (2020) Electric Vehicle Transition in the Mining Industry. Viewed 7 January 2021, <https://globalroadtechnology.com/electric-vehicle-transition-in-the-mining-industry/>.

352 Balinski B (2020) Introducing HyperPower Technologies. Viewed 7 January 2021, <https://www.aumanufacturing.com.au/introducing-hyperpower-technologies>

Roadmap synthesis and summary of investment priorities

The emergence of critical energy minerals represents a unique opportunity for Australia to optimise the connection between its mining, manufacturing and energy sectors. As a starting point, given that the majority of the shortlisted critical minerals generally exist in smaller deposits compared to major minerals such as iron ore, it is incumbent on the mining sector to embrace innovative and more flexible mining processes to ensure their economic viability. This can include improvements in assurance over ore deposits as well as the development of bespoke processing that draws on more efficient collaborations between industry and the research community.

However, as the majority of the technologies expected to undergo accelerated growth rely on electrochemical and direct mechanical (as opposed to thermal) electricity generation, the key point of connection is in the production of high purity materials that are required to support the energy transition. This represents a departure from mass production of lower purity materials for the steel sector which have dominated the mining industry to date. Investment in high purity materials is also likely to:

- improve access to finance for miners via stronger and more direct relationships with technology OEMs
- create further synergies between processing operations (e.g. greater use of by-products)
- increase the scope for resource circularity via centralised metallurgical processing of both virgin and recycled materials
- help position Australia as a major global supplier to a wider range of high-tech markets.

In order to then move further downstream, several primary barriers arise in the Australian context. These include:

1. **Customer location:** For most of the shortlisted energy technology value chains, production of high specification materials and their associated powders, alloys and components will require know-how and IP that exists in overseas jurisdictions. However, OEM decisions regarding licensing and investment in new regions are likely to depend on proximity to large consumer markets and the availability of dedicated RD&D precincts to enable continuous technological improvement.

2. **High cost of energy:** Particularly on the east coast of Australia, the cost of energy continues to remain high which represents a barrier to cost competitive mining and manufacturing due to the price sensitivity of relevant processes.

3. **Willingness to pay a premium:** The potential to supply sustainably sourced materials is a key comparative advantage for Australia. However, compliance with various sustainability measures and frameworks typically increases the cost of production. There is considerable conjecture over the willingness of OEMs to pay the consequent premium, particularly as they seek to levelise the cost of emerging energy technologies with fossil fuel incumbents.

However, there are a number of key enablers that have the potential to kickstart a positive feedback loop supporting local investment in Australia. This is illustrated in Figure 24 and summarised further below.

Local energy demand

Although Australia's primary focus is on global energy technology supply chains, it is important not to underestimate the potential for local demand for renewable energy technologies in de-risking investment in domestic manufacturing. This includes the additional capacity required to support a potential renewable energy export industry (i.e. via energy carriers such hydrogen). The most efficient mechanism to ensure the necessary investment is to implement staggered local content quotas that have an initial focus on scaling local manufacturing, followed by subsequent requirements on locally produced materials. This can also foster the development of dedicated R&D and manufacturing precincts for each of the technology value chains.

Low-cost renewable energy

The economies of scale expected to be achieved via local uptake of renewable energy technologies, particularly for energy export, is likely to place significant downward pressure on technology capital costs and the overall cost of energy.

Competitive sustainable products

Integration of low-cost renewable energy is one of the primary means by which Australian mining and manufacturing proponents can produce sustainable outputs with a reduced premium. Given that the mining sector already represents 10% of Australia's total energy use, this could result in another step change increase in local renewable energy demand.[353]

353 SunSHIFT (2017) Renewable Energy in the Australian mining Sector: White paper. ARENA, Australia.

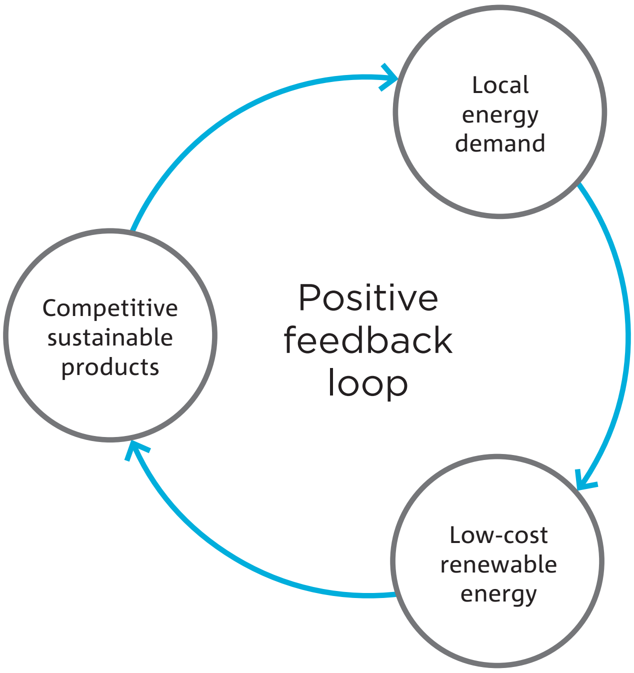

Figure 24: Positive feedback loop connecting mining/ manufacturing and energy sectors

Solar PV

The criticality of the underlying minerals, comparative strengths on either end of the value chain and significant local demand creates considerable potential for a local solar PV manufacturing industry in Australia.

Upstream, there is increasing domestic activity in development of HPQ deposits required to produce solar grade silicon metal. This is particularly important considering the current state of the global industry wherein two companies, both operating mines in the US, are responsible for the majority of the world's HPQ supply. Should these HPQ deposits be developed, Australia also has a natural abundance of biomass derived charcoal that can be used to produce high purity silicon metal without the introduction of other contaminants.

A key enabler of the upstream portion of the solar PV supply chain will be to vertically integrate HPQ extraction through to production of polysilicon (i.e. 9–11N purity silicon). As a higher value intermediate product, production of polysilicon can help de-risk investment in local HPQ resources, promote longer term utilisation of recycled silicon and further the potential to supply other semiconductor markets. Given the absence of an existing industry, this is likely to require partnerships with established manufacturers overseas, integration of low-cost renewable energy and longer term development of polysilicon production processes with a reduced energy and environmental footprint.

Despite this, domestic polysilicon production is still expected to command a premium over other low-cost jurisdictions which adversely impacts the competitiveness of locally produced of wafers, cells and modules. Alongside automated production lines, the most effective means by which this premium can be reduced is by leveraging Australia's leading capabilities in design of high efficiency solar cells and modules to produce a competitive levelised cost of electricity. This includes ongoing efforts to increase cell efficiencies and displace more expensive materials such as silver with copper as a lower cost alternative. Further, should degradation issues continue to be overcome, additional improvements in efficiency could be achieved via the layering of perovskite to form silicon tandem cells.

Excluding the scale of solar PV required to support a hydrogen export industry, local cumulative deployment in Australia is expected to be in the order of 100 GW by 2050 with limited scope for use of recycled silicon. The imposition of local content quotas to support the expected level of deployment will therefore be a key enabler of investment in local manufacturing and ongoing R&D. Design of R&D incentives that encourage translation of early stage cell and module designs to locally manufactured end products will also be critical in ensuring a competitive domestic solar value chain.

Wind

There is significant potential for Australia to develop domestic supply chains to support deployment of wind turbines. Of the discrete system components, while the generator shows the greatest potential to utilise Australia's critical minerals endowment, blades and towers also represent favourable opportunities for local manufacture.

The generator, which is one of most important system components in terms of performance, relies on the use of Neodymium-Iron-Boron (NdFeB) permanent magnets derived from REEs. However, wind turbines represent a comparatively small market for permanent magnets (compared to applications such as electric vehicle motors) and are therefore unlikely to be the primary driver for a domestic REE value chain. This is particularly the case for the Australian market due to the likely roll out of 2-stage geared turbines (onshore) as opposed to direct-drive turbines (offshore). The latter has a higher permanent magnet content but is more likely to see significant growth in Europe, Asia and the US.

With this, there may be opportunities for the wind sector to provide an additional localised offtake as part of a broader strategic investment in an Australian permanent magnet supply chain. While Australia is endowed with a rich supply of REE deposits and retains the technical capabilities needed to deploy local rare earth oxide (REO) separation facilities, it is industry concentration offshore and consequent price benchmarking that presents the primary barrier to investment.

One of the more important means by which this can be overcome is to vertically integrate REE extraction through to production of magnet metals. This will enable supply of a higher value product into a broader range of markets and increases the scope for centralisation of metallisation facilities (for virgin and recycled materials) to improve economies of scale.

Beyond metallisation, permanent magnet production requires dedicated manufacturing facilities specifically for wind generators and investment in local production will require partnerships with major OEMs or third party generator suppliers. The same partnership requirements will extend to other nacelle components such as power converters and control equipment.

Although not underpinned by critical minerals, there is a unique opportunity to capitalise on leading Australian developments in advanced carbon fibre composites to further industry moves towards increased blade lengths. Australia also retains the capacity to scale production of towers which comprise primarily of low complexity steel. In contrast, rotor hubs require chromium and nickel based alloys and significant investment will be needed to develop chromium resources and downstream alloy metal processing.

CSP

CSP, namely Central Tower configurations, are expected to become a more competitive form of renewable energy generation as greater value is placed on dispatchable (as opposed to variable) electricity generation. Increasing investment in the electricity sector is then likely to further the potential for integration of CSP in high temperature applications across a number of industries including minerals extraction and processing.

CSP represents the only renewable energy technology (shortlisted in the Roadmap) that relies on thermal energy generation. As such, there is an ongoing requirement for lower purity metal alloys consisting of nickel, magnesium, manganese, vanadium and chromium. While Australia is a primary producer of some of these metals (e.g. nickel and manganese), there is currently limited local alloy production and that is unlikely to shift as a consequence of an emerging global CSP industry.

Rather, although not underpinned by critical minerals, IP key to the development of CSP plants relates primarily to the design of heliostats given the quantities required for a single asset and their impact on overall cost. Emerging Australian companies are currently leading developments in this area through the optimisation of heliostat design that can withstand harsh conditions with reduced volumes of material. Despite these developments, while heliostats have a higher value once assembled (as opposed to underlying materials), CSP OEMs are likely to continue to commercialise their heliostat IP by partnering with local material suppliers and manufacturers in Australia and overseas. This is due to the poor packing density and fragility of these units which makes them cost prohibitive to distribute.

Australia is also leading development of thermal energy storage systems that utilise phase change materials comprising other critical minerals such as graphite and aluminium. While applicable to other forms of variable renewable electricity generation, these systems are particularly relevant to CSP as the industry moves towards higher temperatures (i.e. 800–1000°C) for both electricity generation and high temperature processing. They are also modular, making them applicable to a wide range of heat/energy storage applications. Importantly for Australia they can be containerised and shipped offshore.

Batteries

Australia has significant potential to build battery capabilities across the value chain. Current efforts are ongoing to scale both the upstream and downstream portions separately, which could lead to an integrated supply chain in the medium- to long-term.

Upstream, Australia is a major producer of many of the primary raw materials (e.g. lithium, nickel and manganese) that underpin mature battery chemistries. The opportunity for vertically integrated production of electrodes (i.e. anodes and cathodes) will also likely see continued development of domestic cobalt, phosphorous, graphite and vanadium deposits despite more modest activity to date. Production of electrode materials represents a significant opportunity to develop a higher value intermediate product that can increase supply chain diversity for global battery OEMs and further the potential for downstream battery manufacture in Australia.

One of the primary barriers to domestic manufacture however is that battery materials are subject strict specifications and complex patents held offshore which can increase approval delays and costs for local proponents. For Australia to build competitive production facilities, strategic investment apportioned across both mature and emerging battery technology development is therefore likely to be required.

For mature battery chemistries, given the availability of the underlying materials within a proximate region, there is a unique opportunity to build battery hubs (for both primary production and recycling) and centres of excellence to support ongoing development. Such initiatives can capitalise on existing efforts to develop certification labs, help attract OEMs to set up operations onshore and commercialise battery cells and packs that are suitable for the Australian climate.

At the same time, to reduce long term dependency on global OEMs, there is also potential to increase R&D on next generation battery chemistries (e.g. lithium-metal). Despite smaller R&D budgets (compared to regions such as the EU and US), Australia has a strong precedent for developing step change improvements in mature battery technologies, as seen previously with the lead-acid 'Ultra-battery'.

Hydrogen

Compared to other energy technology value chains, the global hydrogen industry is relatively nascent. Consequently, there is considerable scope for Australia to ramp up investment in new supply chains, particularly in support of the opportunity to become a leading global hydrogen producer.

Fuel cells used in vehicles represent one of the more mature end-use applications with OEMs already deploying industrialised manufacturing facilities adjacent to emerging markets overseas. The challenge for local fuel cell manufacture in Australia is compounded by reliance on platinum as the primary critical metal due to limited domestic resources and the high cost of entry for platinum based catalyst production.

A different scenario presents in relation to electrolysis given that it underpins Australia's opportunity to export hydrogen and retain its role as a primary energy exporter through the energy transition. Such developments will also likely further the potential for hydrogen use across a number of domestic sectors such as transport. Of the mature forms of electrolysis, PEM has the least established global supply chain which increases the scope for local manufacture in Australia. Alongside aerospace and defence technologies, PEM electrolysis provides another source of demand for locally produced titanium metal.

The key IP held by prominent PEM electrolysis OEMs relates to the integration of stack components. However, the underlying components are relatively easy to manufacture and partnering with these OEMs to deploy production facilities onshore can create new opportunities for local suppliers. Early engagement with OEMs could ensure PEM design specifications are suitable to the Australian climate and promote ongoing R&D investment in titanium based additive manufacturing, alternative (to platinum) catalysts and more durable components. Current efforts among OEMs to industrialise and automate stack manufacture will also help minimise the impact of higher Australian labour costs. Conversely, PEM electrolysis BoP is typically 'off-the-shelf' and the imposition of local content quotas will likely ensure that demand is met by Australian manufacturers.

Lastly, one of the primary challenges regarding hydrogen export relates to finding suitable high volumetric density hydrogen carriers to improve the economics of hydrogen distribution. Given that ammonia is likely to play a key role as a hydrogen carrier, Australia is leading developments in direct ammonia synthesis (via electrolysis) that by-passes the need for the conventional Haber-Bosch process. Should existing barriers to development be overcome, localised manufacture of direct ammonia synthesis is also likely to continue to draw on advances in titanium extraction and processing.

Appendix A
Australia's critical minerals potential: detailed assumptions

Electricity demand is based on the 'High VRE' scenario presented as part of the GenCost project undertaken by CSIRO and AEMO in December 2020.[354]

A list of the minerals underpinning the above technologies was compiled. Their criticality was then assessed according to the following criteria and tiers set out below in Table 7.

For the shortlisted critical minerals, the mineral intensity factors (t/GW) were compiled as per Table 8 and multiplied by the forecast demand in Table 6 to determine the total volumes of minerals required for the energy transition as set out in Figure 25.

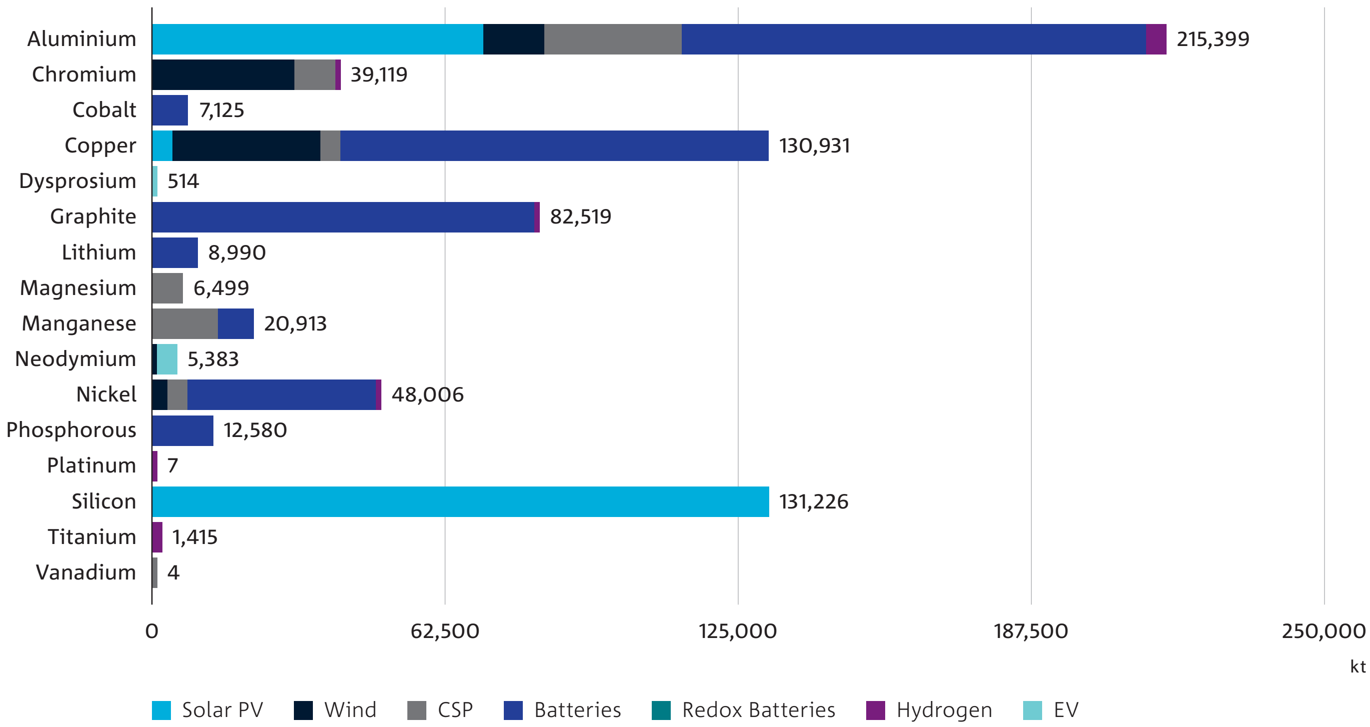

Figure 25: Total cumulative minerals demand for new installed capacity to 2050 based on modelled installed capacity

354 Graham P et al. (2020) GenCost 2020–21: Consultation Draft. CSIRO, Australia.

Table 6: Cumulative new installed capacity from 2020 to 2050

Energy technology	Sub-technology	New installed capacity (GW)	Assumptions
Solar PV	Crystalline silicon	4,038	100% of solar PV will be crystalline silicon panels.
Wind	Geared	4,282	100% of onshore installations will be geared turbines.
	Direct-drive	2,336	100% of offshore installations will be direct-drive turbines.
CSP	Central Tower	2,500	100% of CSP will be Central Tower plants.
Batteries	LiNMC	56,669 (GWh)	70% of stationary and EV batteries will be LiNMC, with LiNMC 622 accounting for this from 2020 to 2029 and LiNMC 811 from 2030 to 2050.
	LFP	24,285 (GWh)	30% of stationary and EV batteries will be LFP.
	Redox Batteries	0.01	-
Hydrogen	PEM Fuel Cell	13,702	-
	AE Electrolyser	730	-
	PEM Electrolyser	5,257	-
EVs	Total BEV and FCEVs	1,679,123,401 (# of vehicles)	-

Table 7: Three tiers of critical energy minerals

Tier 1		
High demand from energy technologies, *AND* Listed as critical by all key trading partners[355]	Carbon (Graphite) Cobalt Lithium	Platinum Group Elements (PGEs) Rare Earth Elements
Tier 2		
High demand from energy technologies, listed as critical by some key trading partners *OR* Lower demand from energy technologies, listed as critical by all key trading partners	Aluminium Chromium Copper Magnesium Manganese	Titanium Nickel Phosphorus Silicon Vanadium
Tier 3 – Excluded from Critical Energy Minerals Roadmap		
Low demand from energy technologies, *AND* Listed as critical by some key trading partners or not listed as critical	Boron Iridium Iron Molybdenum	Silver Zinc

355 DIIS and ATIC (2019) Australia's Critical Minerals Strategy 2019.; USGS (2018) Interior Releases 2018's Final List of 35 Minerals Deemed Critical to U.S. National Security and the Economy. Viewed 3 September 2020, <https://www.usgs.gov/news/interior-releases-2018-s-final-list-35-minerals-deemed-critical-us-national-security-and>; European Commission (2020) Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability. <https://ec.europa.eu/docsroom/documents/42849>.

Table 8: Mineral intensities for critical energy minerals

Technologies	Mineral Intensity (t/GW)															
	Al	Cr	Co	Cu	Dy	C	Li	Mg	Mn	Nd	Ni	P	Pt	Si	Ti	V
Solar PV																
Crystalline silicon	17,500[356]	-	-	884[357]	-	-	-	-	-	-	-	-	-	32,500[356]	-	-
Wind																
Geared	1,900[356]	4,500[356]	-	4,982[357]	3.25[358]	-	-	-	-	50[358]	377[357]	-	-	-	-	-
Direct-drive	1,750[356]	4,500[356]	-	4,700[357]	13[357]	-	-	-	-	200[357]	377[357]	-	-	-	-	-
CSP																
Central Tower	12,000[359]	3,700[359]	-	1,400[359]	-	-	-	2,600[359]	5,700[359]	-	1,800[359]	-	-	-	-	2[359]
Batteries																
LiNMC 622	987[360]	-	214[361]	1,200[361]	-	966[362]	126[361]	-	200[361]	-	641[361]	-	-	-	-	-
LiNMC 811	854[360]	-	94[361]	1,200[361]	-	984[362]	111[361]	-	88[361]	-	750[361]	-	-	-	-	-
LFP	1,977[360]	-	-	970[360]	-	1,056[362]	102[360]	-	-	-	-	518[360]	-	-	-	-
Redox	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2,920[363]
Hydrogen																
PEM Fuel Cell	300[364]	-	-	-	-	100[364]	-	-	-	-	-	-	0.075[364]	-	-	-
AE Electrolyser	-	45[364]	-	-	-	-	-	-	-	-	76[364]	-	-	-	-	-
PEM Electrolyser	-	10[364]	-	-	-	-	-	-	-	-	17[364]	-	1.194[364]	-	269[364]	-
EV																
EV motors	-	-	-	-	0.00028[363]	-	-	-	-	0.0028[363]	-	-	-	-	-	-

356 Ashby M (2013) Materials for low-carbon power. M Ashby (ed.) Materials and the Environment. Elsevier, UK.

357 Manberger A et al. (2018) Global metal flows in the renewable energy transition: Exploring the effects of substitutes, technological mix and development. Energy Policy. DOI: 10.1016/j.enpol.2018.04.056.

358 Rare Earth Elements for geared turbines are assumed to be 25% of direct-drive mineral intensity as stated in Pavel C et al. (2017) Substitution strategies for reducing the use of rare earths in wind turbines. Resources Policy. DOI: 10.1016/j.resourpol.2017.04.010.

359 Phil E et al. (2012) Material constraints for concentrating solar thermal power. Energy. DOI: 10.1016/j.energy.2012.04.057.

360 CSIRO calculations based on data from UBS (2017) UBS Evidence Lab Electric Car Teardown – Disruption Ahead? UBS Limited.

361 Olivetti E et al. (2017) Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals, Joule DOI: 10.1016/j.joule.2017.08.019.

362 Dai Q et al. (2018) Update of bill-of-materials and cathode materials production for lithium-ion batteries in the GREET® model. Argonne National Laboratory, US.

363 Moss R et al. (2013) Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector, JRC Scientific and Policy Reports. European Commission, The Netherlands.

364 CSIRO calculations based on data from Zhao G et al. (2020) Life cycle assessment of H2O electrolysis technologies, International Journal of Hydrogen Energy, DOI: 10.1016/j.ijhydene.2020.05.282.

Table 9: Benchmark critical energy metal prices

	Benchmark price (t AUD)	Traded material	Global opportunity size (AUD billions)	Source
Aluminium	2,896	Aluminium ingot	623.84	[365]
Chromium	14,522	Chromium	568.09	[365]
Cobalt	58,748	Cobalt	418.59	[365]
Copper	7,912	Copper	1,035.88	[365]
Dysprosium	289,143	Dysprosium	148.75	[366] (2019 price only)
Carbon	2,139	Graphite flake	176.47	[365]
Lithium	16,408	Lithium Carbonate Equivalent	147.50	[365]
Magnesium	6,597	Magnesium Metal	42.87	[365] (2019 price only)
Manganese	2,932	Manganese Metal	61.31	[365]
Neodymium	65,466	Neodymium	352.40	[366] (2019 price only)
Nickel	16,078	Nickel	771.83	[365]
Phosphorous	99	Phosphate Rock	1.25	[365]
Platinum	41,477,560	Platinum	303.06	[365]
Silicon	3,482	Silicon Metal	456.92	[365]
Titanium	12,657	Titanium Sponge Metal	17.91	[365]
Vanadium	26,069	Vanadium Pentoxide	0.11	[365]

To determine the global value of each metal in light of the energy transition, benchmark prices were calculated as an average price from 2015–2019 (where possible) and multiplied by the total forecast metal volumes. A conversion rate of 1 USD to 0.7332 AUD was applied.

365 USGS (2020) Mineral Commodity Summaries 2020.

366 2019 estimated price; Office of the Chief Economist (2019) Outlook for Select Critical Minerals in Australia. Department of Industry, Innovation and Science, Australia.

Appendix B
Critical minerals assessment

Aluminium

Aluminium is primarily utilised in the transport (28%) and construction (23%) sectors.[367] With respect to the energy sector specifically, aluminium is used across all of the shortlisted energy technologies. Modelling undertaken as part of this analysis has shown that these technologies (excluding EV vehicle bodies and electricity transmission) could require up to 215 Mt of aluminium by 2050. However, this is unlikely to place significant strain on global resources.

Australia currently holds 18% (5,292 Mt) of global bauxite EDR and in 2019, produced 28% of the world's bauxite (ore containing aluminium). However, Australia's share of production declines when moving downstream, wherein it produced 15% of the world's alumina, and only 2% (1,570 kt) of the world's primary aluminium in the same year. Conversely, China holds 3% of EDR and produces 20% of global bauxite, but supplies over half of the world's alumina and primary aluminium.[368]

With this concentration risk, there may be scope for Australia to expand its aluminium production industry. However, aluminium production from alumina is an energy intensive process and Australian producers have struggled to remain viable with only a few vertically integrated enterprises remaining.[369] Therefore, integration of cheaper energy may provide an opportunity for Australia to return to being competitive with other international suppliers.

Other key risks likely to dampen demand for primary aluminium production include robust resource circularity. Today approximately one-third of total aluminium is produced from recycled material (as opposed to virgin material) and this is expected to grow to 50% by 2050.[370]

Chromium

Chromium is used to form metal alloys that are resistant to heat, abrasion, corrosion and oxidation, and is therefore widely used as a steel alloy in wind turbine rotors, CSP and PEM electrolysers. Cumulative demand from energy these technologies to 2050 is 39,119 kt.

Global chromite EDR were quoted at 570,154 kt in 2019 (~174,000 kt of chromium)[371] with production primarily driven by South Africa (39%), followed by Turkey, Kazakhstan and India.[372] However, South Africa's position in the market may be at risk due to increasing labour and electricity costs, unreliable electricity supply and challenges associated with deep mining as surface deposits become depleted.[372] A market shift away from South Africa may provide an opening for other producers.

Globally, virtually all chromium supply is extracted from dedicated chromite ore.[373] While Australia currently has no local chromium production, EDR were reported at 534 kt in 2019. However, the investment required to restart primary extraction is likely to be significant given the degree of industry development still required.[374] That said, Australian chromite deposits are directly associated with PGEs, creating potential to enhance economic viability of chromite ore and consolidate exploration efforts.[375] There is also potential to recover chromium as a by-product of nickel, but this is unlikely to be cost competitive given that the grade is well below that of chromite deposits.[375]

367 Office of the Chief Economist (2020) Resources and Energy Quarterly, September 2020. Department of Industry, Science, Energy and Resources, Australia.

368 USGS (2020) Mineral Commodity Summaries 2020.

369 Aravanis J (2020) Aluminium Smelting in Australia Industry. Viewed 24 September 2020, <https://my.ibisworld.com/au/en/industry/c2132/industry-performance>.

370 Bertram M et al. (2020) A regionally-linked, dynamic material flow modelling tool for rolled, extruded and cast aluminium products. Resources, Conservation and Recycling. DOI: 10.1016/j.resconrec.2017.05.014; Levi P et al. (2020) Aluminium – Tracking report. International Energy Agency, US.

371 Reserves are reporting in kT of chromite ore of roughly 45% Cr2O3 (note USA and Finland report lower grades, does not materially affect estimate for contained Cr).

372 USGS (2020) Mineral Commodity Summaries 2020.

373 Huston D and Brauhart C (2017) Critical commodities in Australia: an assessment of extraction potential from ores. Geoscience, Australia.

374 Senior A et al. (2020) Australia's Identified Mineral Resources 2019. Department of Industry, Science, Energy and Resources, Australia.

375 Barnes S (2013) Deformed Chromite Layers in the Coobina Intrusion, Pilbara Craton, Western Australia. Economic Geology 108(2), 337–354.

Cobalt

Global cobalt EDR were reported at 7,188 kt in 2019 (versus 7,125 kt expected cumulative demand for energy technologies to 2050). In 2017, 28% of the cobalt produced was used in batteries compared to other primary applications such as superalloys, tools and hard materials.[376] Further, despite holding 19% (1,399 kt) of EDR, Australia supplied 4% (5,700 t) of the world's cobalt, primarily produced as a by-product of nickel.

The critical nature of cobalt stems from the concentration of supply in the Democratic Republic of Congo (DRC) which is estimated to hold approximately 50% of global EDR and is responsible for 70% of production.[377] Adding to this is the accompanying sovereign risk, wherein the DRC is ranked lowest in terms of political stability relative to other mining countries.[378] There are also environmental and social risks to be considered as the DRC continues to struggle with human rights issues in its artisanal and industrial mining operations.[379]

With expected growth in demand for batteries, there has been an increased focus on responsible value chains by international bodies such as the London Metal Exchange (LME) and the Global Battery Alliance.[380] This may result in a greater diversification of supply by key OEMs and increase the scope for other countries such as Australia to ramp up production.

While Australia is deemed to have a large cobalt resource, extraction from its dominant deposit type is economically challenging.[381] For instance, the Central African Copperbelt that runs through the DRC hosts copper deposits that typically have a high grade of cobalt (0.1%–0.4%).[382] Conversely, Australia has relied on cobalt extracted as a by-product of nickel mining, with concentrations between 0.05%–0.15%.[382] However, reliance on nickel production from laterites could improve the economics of both cobalt and nickel extraction given that laterites have a higher cobalt to nickel ratio (than sulphide deposits).[383]

Australia's potential to increase cobalt production could also stem from prospective copper, gold and cobalt deposits. Operating a prospective mine in NSW, Cobalt Blue is one proponent undertaking a feasibility study over this deposit type with a view to producing 3,500 t of cobalt per year over an operating life of 20 years.[384]

As mentioned, there are ongoing efforts to reduce the cobalt content in LiNMC batteries due to both its cost and potential supply risks. However, with some uncertainty regarding the performance of LiNMC811 and investment in existing supply chains by OEMs such as LG Chem and Samsung SDI, the risk posed to cobalt producers in the short term (2020–2030) is relatively low. Longer-term, cost competitive cobalt supplies outside of the DRC could also minimise the imperative to deploy alternative battery chemistries.

Copper

Copper is a widely used major metal with applications as an electrical conductor, heat exchanger, and as a key input material for telecommunications and plumbing. With respect to the energy transition, copper is used across batteries, CSP, solar PV and wind and demand from these technologies to 2050 is projected to require 130,931 kt, compared to the 20,288 kt produced in 2019 and 877,356 kt in global EDR. Notably, although outside the scope of this report, one of the primary drivers of copper demand is likely to be in the deployment of transmission and distribution infrastructure to accommodate more distributed energy generation assets.[385] The same is true of electric vehicles which are likely to require three times the amount of copper compared to ICEs.[386]

376 Azevedo M et al. (2018) Lithium and cobalt – a tale of two commodities. McKinsey & Company.

377 USGS (2020) Mineral Commodity Summaries 2020.

378 Van De Brink S et al. (2020) Identifying supply risks by mapping the cobalt supply chain. Resources, Conservation and Recycling. DOI: 10.1016/j.resconrec.2020.104743.

379 Sovacool B (2019) The precarious political economy of cobalt: Balancing prosperity, poverty and brutality in artisanal and industrial mining in the Democratic Republic of the Congo. The Extractive Industries and Society. DOI: 10.1016/j.exis.2019.05.018.

380 Elkind EN et al. (2020) Sustainable Drive Sustainable Supply: Priorities to Improve the Electric Vehicle Battery Supply Chain. Berkeley Center for Law, Energy & the Environment, US.

381 Mudd GM et al. (2013) Quantifying the recoverable resources of by-product metals: The case of cobalt. Ore Geology Reviews. DOI: 10.1016/j.oregeorev.2013.04.010.

382 Cobalt Institute (2020) Ores Containing Cobalt. Viewed 9 September 2020, <https://www.cobaltinstitute.org/ores-containing-cobalt.html>; Hitzman MW et al. (2017) Cobalt – Styles of Deposits and the Search for Primary Deposits, USGS, US; Brink S et al. (2020) Identifying supply risks by mapping the cobalt supply chain. Resources, Conservation and Recycling. DOI: 10.1016/j.resconrec.2020.104743.

383 Best A and Vernon C (2020) State of Play: Australia's Battery Industries as at March 2020. CSIRO, Australia; Campagnol N et al. (2017) The future of nickel: A class act. McKinsey & Company.

384 AMEC (2020) Investment Opportunities: Australia's Critical Minerals.

385 Schipper BW et al. (2018) Estimating global copper demand until 2100 with regression and stock dynamics. Resources, Conservation and Recycling. DOI: 10.1016/j.resconrec.2018.01.004.

386 Reuters (2017) Copper demand for electric cars to rise nine-fold by 2027: ICA. Viewed 15 January 2021, <https://www.reuters.com/article/us-copper-demand-electric-vehicles-idUSKBN1940PC>.

Other copper dependent industries are also projected to grow significantly, placing additional strain on supply.[387] The critical nature of copper is then extended when considering the longevity of global copper mining (over 10,000 years) which has led to declining ore grades and the need for deeper exploration to uncover new deposits.[388] Further, China continues to grow refining capacity following the shutdown of smelters in other countries, increasing the risk of market concentration.[389]

Although Australia ranks second in global EDR (11% or 93,356 kt), it ranks sixth in production (5% or 938 kt), which may present an opportunity to expand the local industry.[390] Notably, most copper containing ore in Australia is produced from underground mines, a point of differentiation from other major producers that rely on open-cut methods.[391] While underground mining typically has a higher capital cost, it may extend Australia's comparative advantage as global surface deposits continue to deplete. Copper is also often associated with other minerals likely to see increased demand from the energy transition (e.g. cobalt), which may improve the economics of extraction.

Note that whereas some of Australia's major copper deposits are associated with potentially toxic materials (e.g. lead at Mount Isa and uranium at Olympic Dam),[392] other notable deposits including Prominent Hill (SA) and Girilambone (NSW) do not face the same sustainability considerations.[393]

There is potential for aluminium to substitute copper in some electrical equipment and power cables. However, this demand risk is low considering that aluminium has a lower conductivity which has an adverse impact on performance.[394] Further, given the expected increase in copper demand, high recovery rates and increased copper recycling is likely to aid rather than disrupt primary supply.

Graphite

Both natural and synthetic graphite are used in the production of LiB anodes. Synthetic graphite, which is derived from petroleum coke or coal-tar, is more costly than natural (mined) graphite flakes due to the energy intensity of production and has a more adverse environmental impact due to the associated emissions. Notwithstanding this, synthetic graphite provides greater consistency in terms of purity which can be critical to enhanced battery performance and relative ease by which it can be made to fit OEM specifications.[395] Consequently, as at 2018, natural and synthetic graphite comprised a 45% to 55% split respectively in demand from battery anodes.[396] Note also that although small amounts of graphite are currently used in the bipolar plates of fuel cells for transport, there is a shifting focus towards metallic alternatives such as stainless steel and titanium.[397]

Given the environmental impact associated with synthetic graphite, Australia is more likely to direct investment towards natural graphite production. Although there is some conjecture, Australia's graphite resources were reported to be in the order of 7,968 kt in 2019. There is also no existing local production. Global natural graphite resources are in the order of 307,868 kt, with major resources located in Brazil, China, Mozambique, Tanzania and Turkey.[398] Notably, China produced over 60% of natural graphite and is responsible for processing all of the world's graphite for LiBs.[399] This creates scope for more strategic diversification of supply by OEMs across Europe, Asia and the US.

387 Schipper BW et al. (2018) Estimating global copper demand until 2100 with regression and stock dynamics. Resources, Conservation and Recycling. DOI: 10.1016/j.resconrec.2018.01.004.

388 Kerr R (2014) The coming copper peak. Science. DOI: 10.1126/science.343.6172.722.

389 USGS (2020) Mineral Commodity Summaries 2020.

390 Senior A et al. (2020) Australia's Identified Mineral Resources 2019. Department of Industry, Science, Energy and Resources, Australia.

391 Geoscience Australia (2013) Copper. Viewed 2 November 2020, <https://www.ga.gov.au/scientific-topics/minerals/mineral-resources-and-advice/australian-resource-reviews/copper>; Fiscor S (2010) Major Open-Pit Copper Mines Move Underground. Engineering and Mining Journal. Viewed 2 February 2021, <http://www.womp-int.com/story/2010vol05/story026.htm>.

392 Skirrow RG et al. (2013) Critical commodities for a high-tech world: Australia's potential to supply global demand. Geoscience Australia, Australia.

393 Geoscience Australia (2019) Copper. Viewed 4 February 2021, <http://www.ga.gov.au/education/classroom-resources/minerals-energy/australian-mineral-facts/copper>.

394 Radetzki M (2009) Seven thousand years in the service of humanity—the history of copper, the red metal. Resources Policy. DOI: 10.1016/j.resourpol.2009.03.003.

395 Asenbauer J et al. (2020) The success story of graphite as a lithium-ion anode material – fundamentals, remaining challenges, and recent developments including silicon (oxide) composites. Sustainable Energy Fuels. DOI: 10.1039/D0SE00175A; Dunn J et al. (2015) Material and energy flows in the production of cathode and anode materials for lithium ion batteries. Argonne National Lab, US. DOI: 10.2172/1224963.

396 Battery University (2019) BU-309 How does Graphite Work in Li-ion? Viewed 15 January 2021 <https://batteryuniversity.com/learn/article/bu_309_graphite>.

397 Song Y et al. (2020) Review on current research of materials, fabrication and application for bipolar plate in proton exchange member fuel cell. International Journal of Hydrogen Energy. DOI: 10.1016/j.ijhydene.2019.07.231.

398 USGS (2020) Mineral Commodity Summaries 2020.

399 Roskill (2019) Graphite: The Race of non-Chinese spherical graphite heats up. Viewed 4 November 2020, <https://roskill.com/news/graphite-the-race-for-non-chinese-spherical-graphite-heats-up/>.

There is also some uncertainty regarding projected demand for natural versus synthetic graphite. While most anodes are expected to use a blend of both, trends towards reduced cobalt content and consequential decreases in battery performance may increase demand for higher purity synthetic graphite. Conversely, given the focus on cost and sustainably produced battery materials, it is expected that natural graphite will still feature strongly as demand increases.

Further, given that the more mature LiB chemistries all require graphite, there is little demand risk in the near term. There is however some suggestion that silicon, which exists in low concentrations in current anodes (i.e. 4–7%), may serve as a potential substitute in the medium to long term. Currently, silicon undergoes significant expansion (roughly 400%) during battery cycling which represents a significant safety hurdle that must still be overcome. Longer term, emerging lithium metal (Li-metal) batteries may see graphite and silicon removed altogether.[400]

Lithium

Lithium is an abundant resource with approximately 19,487 kt in global EDR. Although Australia currently holds 29% (5,702 kt), versus other dominant producing countries such as Chile (44%) and Argentina (9%), it produced 56% (45 kt) of the world's lithium supply in 2019.[401]

The majority of Australia's lithium operations are located in Western Australia, wherein primarily hard rock spodumene deposits are mined and concentrated through conventional methods of crushing, separation and flotation. By comparison, South American resources are primarily salar (i.e. lithium containing brine solution) which is usually pumped out from beneath the earth's surface and left to evaporate in large ponds. Although spodumene mining operations are less costly than brine operations, the product is of lower value due to the additional processing steps required to convert the concentrate to lithium chemicals.

Batteries are expected to be the primary source of demand for lithium, and while current global and Australian EDR theoretically surpass the volumes needed for the energy transition, a significant scale-up in annual production is required. For instance, in 2019, global production was 80 kt, with 46% used in the battery market and the remainder for other applications including ceramics and industrial powders.[402] By 2050, cumulative lithium demand from EV and stationary battery cathodes alone is expected to be in the order of 8,990 kt. An additional 2,625 kt of lithium would be required for lithium fluorophosphate ($LiPF_6$) electrolyte.[403]

The 'criticality' associated with lithium therefore relates more to the potential bottlenecks that stem from low levels of production relative to unanticipated spikes in demand.[404] Australia is likely to be relatively well placed to manage this uncertainty given that spodumene has a higher lithium content and a faster mine ramp rate than brine deposits.[405]

Both spodumene and brine operations have unique environmental impacts that will need to be managed, particularly as demand for lithium increases. For Australia, waste from hard rock lithium sources are likely to present a significant challenge given that 30–50% of the lithium is lost during production of lithium concentrate.[406] A significant effort is therefore likely to be required to improve lithium recovery and position Australia as a sustainable producer.

As discussed in Section 1 Part I, lithium-ion batteries are likely to remain the dominant technology in the short- and medium-term, with some variation in lithium content in the more mature LiNMC, LFP and NCA battery chemistries. Longer term, the adoption of emerging Li-metal batteries have a higher lithium content (i.e. due to use in battery anodes) resulting in a further increase in lithium demand.[407] Further, although prospective sodium and zinc-ion batteries rely on cheaper materials, they are expected to have a lower energy density and may not disrupt demand for lithium from the EV market.

400 Hund K et al. (2020) Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition. World Bank Group, US.

401 USGS (2020) Mineral Commodity Summaries 2020.

402 The batteries figure includes all battery types; Office of the Chief Economist (2020) Resources and Energy Quarterly, March 2020. Department of Industry, Science, Energy and Resources, Australia.

403 Assumptions 18650 Cell, NMC622 variant, 20% oversizing (i.e. 12 kWh of cells for a 10 kWh unit), typical variation between manufacturers +/- 5%.

404 Olivetti A et al. (2017) Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals. Joule. DOI: 10.1016/j.joule.2017.08.019.

405 Flexer V et al. (2018) Lithium recovery from brines: A vital raw material for green energies with a potential environmental impact in its mining and processing. Science of the Total Environment. DOI: 10.1016/j.scitotenv.2018.05.223; Kesler ST et al. (2012) Global lithium resources: Relative importance of pegmatite, brine and other deposits. Ore Geology Reviews. DOI: 10.1016/j.oregeorev.2012.05.006.

406 ANSTO (2020) Minerals expertise advances sustainable lithium ion battery production. Viewed 2 September 2020, <https://www.ansto.gov.au/news/minerals-expertise-advances-sustainable-lithium-ion-battery-production>; Lithium Australia (2019) Lithium ferro phosphate (LFP) as a future energy storage technology. Viewed 15 January 2021, <https://lithium-au.com/wp-content/uploads/2016/11/21112019-Lithium-ferrophosphate-as-a-future-energy-storage-technology.pdf>.

407 Zhang X et al. (2018) Recent Advances in Energy Chemical Engineering of Next-Generation Lithium Batteries. Engineering. DOI: 10.1016/j.eng.2018.10.008.

Magnesium

For CSP, magnesium is used as a steel alloy to improve strength and prevent corrosion at high operating temperatures.[408] Magnesium can be processed from magnesite, dolomite, serpentine, seawater and natural brines, all of which are present in Australia.[409] Australia's current production of magnesite (413 kt in 2019) comprises primarily low purity magnesium compounds (e.g. talc) and small quantities of higher purity products (e.g. magnesium oxide powder).[410]

Magnesium resources are abundant, globally dispersed, and likely to be secure for the long term.[411] However, mining and production of magnesium (both compounds and metal) is concentrated in China (i.e. 82% of global metal production in 2019) and remaining metal production is distributed amongst a number of smaller producers, including Russia (7%), Kazakhstan (2%) and Israel (2%).[411] As market leader, China has significant influence on the global price of magnesium and its precursors, which has led to price increases in recent years as many of their refining facilities were closed on environmental grounds.[412] Further, given that trade primarily occurs directly between producer and manufacturer, there is little transparency over global price which provides another barrier to market entry for smaller producers.[412]

As the majority of current magnesium demand stems from metal alloys in other industries, demand from CSP alone (6,499 kt to 2050) is unlikely to provide new opportunities for Australia to expand production. Significant investment in downstream processing of steel alloys would also be required to support CSP developments.

Manganese

In 2019, global manganese EDR were quoted at 826,000 kt, and Australian EDR at 114,000 kt (14%). Approximately 88% of manganese is used for ferromanganese and silicomanganese alloys.[413] By contrast, only 9% is used to produce electrolytic manganese metal (EMM) and 3% for battery and fertiliser applications.[413] Cumulative demand from energy technologies including batteries and CSP is likely to be 20,913 kt by 2050.

While there is some supply risk given that production occurs predominantly in countries with a degree of political instability (e.g. South Africa), criticality stems primarily from China being responsible for most of the world's manganese ore processing.[414] China also produced 69% of global manganese sulphate output in 2019.[415]

In light of these trends and given the abundance of EDR, there is a significant opportunity for Australia to increase production (from 3,185 kt or 17% of global production in 2019). Whereas ores with 15–35% manganese content are required to demonstrate economic viability, Australia has typically mined grades over 43%.[416] Further, due to the historically low value of manganese, some Australian resources are likely to have been underexplored and understated.[417]

Currently, emerging Australian proponents such as Element 25 are focused on producing manganese concentrate for export in the near term and then production of both high purity EMM and manganese sulphate. In WA, substantial resources have also recently been uncovered which are at surface level and thus easily extracted.[417] It is anticipated that while these deposits are lower grade and perhaps less suitable for steel applications, it may be beneficial for battery chemicals processing if sulphur based compounds are present.[418]

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408 Phil E et al. (2012) Materials constraints for concentrating solar thermal power. Energy. DOI: 10.1016/j.energy.2012.04.057.

409 ATIC (2020) Australian Critical Minerals Prospectus 2020. Department of Industry, Science, Energy and Resources, Australia.

410 Australian production figure based on reported data from South Australia (2018) and Queensland (2017–2018); Senior A et al. (2020) Australia's Identified Mineral Resources 2019. Department of Industry, Science, Energy and Resources, Australia; ATIC (2020) Australian Critical Minerals Prospectus 2020. Department of Industry, Science, Energy and Resources, Australia.

411 USGS (2020) Mineral Commodity Summaries 2020.

412 Office of the Chief Economist (2019) Outlook for Select Critical Minerals in Australia. Department of Industry, Innovation and Science, Australia.

413 Flook R (2019) Manganese: The Black Art. Viewed 11 Feburary 2021, <https://www.element25.com.au/site/PDF/2201665c-04b7-4564-8d89-364cbfb8982a/BenchmarkMineralIntelligenceManganeseTheBlackArt>.

414 Liu B et al. (2019) Extraction and separation of manganese and iron from ferruginous manganese ores: A review. Minerals Engineering. DOI: 10.1016/j.mineng.2018.11.016.

415 International Manganese Institute (2019) ImnI Statistics 2019; QUT (2020) Li-ion battery cathode manufacture in Australia: A Scene Setting Project. FBICRC, Australia.

416 Flook R (2019) Manganese: The Black Art. Benchmark Minerals, Australia.

417 Spinks S et al. (2018) Sedimentary Manganese as Precursors to the Supergene Manganese Deposits of the Collier Group; Capricorn Orogen, Western Australia. CSIRO, Australia.

418 The process of using sulphur or sulphide content to produce in situ sulphuric acid for leaching ores is a well-known mining practice for other metals; McDonald RG and Li J (2020) The High Temperature Co-Processing of Nickel Sulfide and Nickel Laterite sources. Minerals. DOI: 10.3390/min10040351.

As with nickel, manganese is expected to remain an important component of LiB cathodes given its role in reducing susceptibility to thermal runway. Manufacturers such as Tesla have announced an intention to design out cobalt and move to a nickel-manganese cathode (2:1 ratio).[419] Manganese may also be used in next generation Li-metal batteries (albeit at lower volumes).[420]

Nickel

In 2019, global nickel EDR were 90 Mt (versus 48 Mt expected cumulative demand for energy technologies to 2050). Notably, Australia held 24% (21,156 kt) of reported EDR but was responsible for only 6% (155 kt) of production. Other dominant producers include Indonesia, Russia, Canada and New Caledonia.[421]

Given the spread of producers, nickel does not suffer from the same supply concentration risk seen with other shortlisted critical energy minerals. Rather, its moderate criticality stems from projected growth in demand from both the steel and LiB industries. At present, approximately only 5% of nickel produced was for the battery market.[422]

This supply risk is potentially compounded by depletion of economically viable deposits. Currently, nickel is extracted from either sulphide or laterite (oxide) deposits. In the past, sulphides were relied on heavily due to the availability of relatively simple beneficiation methods. However, these deposits are consequently depleting and there is increasing reliance on laterite deposits which are more abundant but contain a variety of other elements, making them more complex and costly to process.[423]

In light of these trends, Australia may be well placed to ramp up nickel production given domestic EDR versus current production levels. Although most local known nickel deposits are laterites (69%), the majority of Australia's nickel production still comes from sulphide deposits.[424] Environmental impacts associated with both deposit types will also need to be addressed. For instance, nickel sulphide deposits can contain arsenic and other toxic heavy minerals that can pollute surrounding water bodies.[425] Conversely, nickel laterite ore processing is more energy intensive (than sulphides) due to the additional processing steps required.[425]

As discussed in relation to cobalt, efforts to develop battery chemistries with reduced or no cobalt will lead to an increase in nickel demand (i.e. 8:1 ratio of nickel to cobalt in LiNMC811 batteries). This is expected to de-risk investment for nickel proponents at least in the short to medium term.

Phosphorus

Phosphorus is found in phosphate rock and is typically reported in its processed form, phosphorus pentoxide (P_2O_5).[426] Global reported EDR are estimated at 70 billion tonnes (i.e. ~9 billion tonnes of phosphorus) and annual production is in the order of 240 Mt.[427] Today more than 80% is used in fertiliser production.[428]

With respect to the energy sector and LiBs specifically, phosphorous is used in both the electrolyte (for most chemistries) and cathode in LFP batteries. Should LFP cathodes make up 30% of the stationary and transport battery market, phosphorus consumed between now and 2050 is expected to be comparatively small at 12,580 kt. The inclusion of lithium fluorophosphate ($LiPF_6$) electrolyte represents an additional 11,713 kt of phosphorus demand.[429]

419 Yavuz R(2020) Manganese: Tesla plans increased use of manganese within cathode chemistry mix for its mid-range EV fleet. Viewed 23 December 2020, <https://roskill.com/news/manganese-tesla-plans-increased-use-of-manganese-within-cathode-chemistry-mix-for-its-mid-range-ev-fleet/>.

420 Yan S et al. (2019) Enhanced Bifunctional Catalytic Activity of Manganese Oxide/Perovskite Hierarchical Core-Shell Materials by Adjusting the Interface for Metal-Air Batteries. ACS Applied Materials and Interfaces. DOI: 10.1021/acsami.9b06141.

421 USGS (2020) Mineral Commodity Summaries 2020.

422 This figure does not include batteries for consumer electronic devices such as laptops and phones; Office of the Chief Economist (2020) Resources and Energy Quarterly, September 2020. Department of Industry, Science, Energy and Resources, Australia.; Olivetti A et al. (2017) Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals. DOI: 10.1016/j.joule.2017.08.019.

423 Khoo JZ et al. (2020) A life cycle assessment of a new laterite processing technology. Journal of Cleaner Production. DOI: 10.1016/j.jclepro.2016.11.111.

424 The only major nickel laterite miner currently operating in Australia is Murrin Murrin produced 39,7171t in 2018.

425 Mudd G (2010) Global trends and environmental issues in nickel mining: Sulfides versus laterites. Ore Geology Reviews. DOI: 10.1016/j.oregeorev.2010.05.003.

426 Mew M et al. (2018) Phosphorus Supply Chain – Scientific, Technical and Economic Foundations: A Transdisciplinary Orientation. Sustainability. DOI: 10.3390/su10041087.

427 Phosphorus (P) inferred at ~13% of phosphate rock and 30% phosphate (P2O5); USGS (2020) Mineral Commodity Summaries 2020; Springer NP (2017) Physical, technical, and economic accessibility of resources and reserves need to be distinguished by grade: Application to the case of phosphorus. Science of the Total Environment. DOI: 10.1016/j.scitotenv.2016.10.190.

428 Geissler B et al. (2018) Striving Toward a Circular Economy for Phosphorus: The Role of Phosphate Rock Mining. Minerals. DOI: 10.3390/min8090395.

429 Assumptions 18,650 Cell, NMC622 variant, 20% oversizing (i.e. 12 kWh of cells for a 10 kWh unit), typical variation between manufacturers +/- 5%.

The criticality of phosphorus is therefore associated primarily with its competing use as a fertiliser to support a growing population and the anticipated concentration of supply. For instance, the United Nations estimates that there will be a 60% increase in food demand by 2050.[430] While primary producing countries today (e.g. China, US, Russia) still hold substantial EDR,[431] there is some concern that further depletion could lead to increasing reliance on Morocco and Western Sahara where 72% of the world's phosphate EDR are currently located.[432]

Australia is a minor supplier of phosphate rock. It currently possesses less than 2% of global EDR (1,091 Mt), 93% of which is located in the Georgina basin (QLD and NT).[433] Large amounts of phosphate rock are also found alongside REE deposits, particularly Mount Weld (WA) and Nolans Bore (NT).[434] Australia's highest ore grades are found at Paradise North (28.4%) and Phosphate Hill (25.5%) with the latter also hosting Australia's sole mining and processing facility operated by Incitec Pivot.[435] As phosphate rock requires an average of 30% of P_2O_5 for export, proponents are increasingly looking at ways to beneficiate lower grade ores cost-effectively.[435]

Given the maturity of Australia's phosphate industry and resources, there may be an opportunity to divert supply to support an emerging LiB industry. Although this would require further processing investment for battery grade products (see Section 5.1.1 Part II), this may provide an opportunity to manufacture a higher value product which could improve the economics of local phosphate production.

Platinum

Platinum is part of a broader set of Platinum Group Elements (PGEs) which are typically high value commodities.[436] Primary industrial applications include use as catalytic converters in ICE vehicles to reduce vehicle emissions. Platinum, along with palladium, can be extracted from primary PGE deposits or as a by-product of nickel, copper and some uranium deposits.[437]

Global PGE EDR (69 kt) and platinum production (0.18 kt in 2019) are heavily concentrated in South Africa (i.e. 91% and 72% respectively), with the remainder of significant operations located in Russia and Zimbabwe.[438] All three of these countries retain some degree of sovereign risk. Further, whereas internal combustion engines currently use approximately 3–7 g of platinum per vehicle, FCEVs require ~56 g which may impact long term supply and demand profiles depending on the rate of uptake.[439]

In light of these supply risks, there may be scope for Australia to ramp up local production. While Australia has minor primary PGE EDR (37.6 t) in deposits such as Munni and Panton (both in WA), their volumes may not be high enough to warrant extraction.[440] As a result, platinum production is likely to be dependent on continued extraction as a by-product of nickel (sulphide deposits), and potentially future extraction from copper, chromium and unconformity-related uranium deposits.[437] Note that resources for platinum extraction as a by-product from these primary minerals are likely to be underestimated due to lack of accessible data in primary commodity mine operations.[441]

As has been the case with catalytic converters, there is some risk that palladium, which has historically been priced lower, may substitute platinum in both electrolysers and fuel cells despite reductions in performance.[442] However, platinum and palladium are co-products of the majority of primary PGE deposits and as such, developments in hydrogen technologies may present an opportunity to include both metals separately or as blended catalysts to meet demand.

430 Reuter B et al. (2014) Future Resource Availability for the Production of Lithium-Ion Vehicle Batteries. COFAT 2014, Munich.

431 USGS (2020) Mineral Commodity Summaries 2020.

432 Cooper J et al. (2011) The future distribution and production of global phosphate rock reserves. Resources, Conservation and Recycling. DOI: 10.1016/j.resconrec.2011.09.009.

433 Senior A et al. (2020) Australia's Identified Mineral Resources 2019. Department of Industry, Science, Energy and Resources, Australia.

434 Senior A et al. (2020) Australia's Identified Mineral Resources 2019. Department of Industry, Science, Energy and Resources, Australia; Geoscience Australia (2015) Phosphate. Viewed 26 September 2020, <http://www.australianminesatlas.gov.au/aimr/commodity/phosphate.html>.

435 Geoscience Australia(2013) Australian Resource Reviews: Phosphate. Viewed 11 February 2021, <https://www.ga.gov.au/scientific-topics/minerals/mineral-resources-and-advice/australian-resource-reviews/phosphate>.

436 Mudd G et al. (2017) Critical Minerals in Australia: A Review of Opportunities and Research Needs. Geoscience Australia, Australia.

437 Huston D and Brauhart C (2017) Critical commodities in Australia: an assessment of extraction potential from ores. Geoscience, Australia.

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439 Onstad E (2019) Bosch goes for platinum-light fuel cells. Reuters. Viewed 15 January 2021, <https://www.reuters.com/article/us-platinum-week-bosch-fuelcells-exclusi-idUSKCN1SJ0FG>.

440 Huston D and Brauhart C (2017) Critical commodities in Australia: an assessment of extraction potential from ores. Geoscience, Australia; Senior A et al. (2020) Australia's Identified Mineral Resources 2019. Department of Industry, Science, Energy and Resources, Australia.

441 Senior A et al. (2020) Australia's Identified Mineral Resources 2019. Department of Industry, Science, Energy and Resources, Australia.

442 Antolini E (2009) Palladium in fuel cell catalysis. Energy & Environmental Science. DOI: 10.1039/B820837A.

Rare Earth Elements (REE)

Neodymium is the primary light REE used in permanent magnets for wind turbines and EV motors. Small amounts of praseodymium and heavy REEs such as dysprosium and terbium are also often added to improve performance, particularly in applications where magnets are subject to higher temperatures.[443]

Despite its title, the REE group is relatively abundant. Australia is the fourth largest producer of REE, with 8% (17.7 kt) of global production and is quoted as having the sixth highest EDR (4% or 4,030 kt).[444] Australia is endowed with all principal sources of REE (bastnaesite, monazite and xenotime) and feasibility assessments over REE extraction from phosphate-uranium deposits are also underway.[445] Further, some Australian REE deposits are reported to have comparatively high neodymium and dysprosium content, as demonstrated in Hastings Technology's Yangibana Project.[446] Xenotime deposits such as Northern Minerals' Browns Range are also rich in higher value heavy REEs.[446]

The 'criticality' of REEs therefore stems more from the majority of mineral processing occurring in China, specifically the steps from REE concentrate to metals (as shown in Figure 26). China currently holds 38% of global REE EDR (predominantly in bastnasite deposits), but produces 85% of all REOs and 98% of heavy REOs.[447] This level of concentration and established infrastructure enables China to set the benchmark global REO price, making it difficult for other nations to set up and sustain domestic processing operations. China is also responsible for 90% of global production of rare earth metals.[447]

Although it is generating significant interest, there are currently no commercial REO separation operations in Australia.

With respect to the environment, cracking and leaching of REE ores releases radioactive material which can have an adverse impact on ground and surface water if not managed appropriately. Further, the processing of REEs is water and energy intensive compared to other minerals.[448]

Currently, there are efforts to reduce the content of REE within energy technologies due to their high cost and supply risks.[449] Substitution in EVs has been an industry focus, with leading manufacturer Tesla developing REE free motors in some of their electric vehicles.[450] However, replacement with non-permanent magnet materials will increase vehicle weight and reduce efficiency.

Similarly, attempts to limit or remove permanent magnets in direct-drive wind turbines have resulted in considerable performance losses.[449] Rather, the key substitution risk for REEs in offshore wind technology is the continued deployment of 2-stage geared turbines and improvements in their ability to operate in higher wind speeds (i.e. offshore). Such turbines require approximately 25% of the permanent magnet content currently used in direct-drive systems.[449]

Figure 26: Stages of REE processing

443 Du X and Graedel T (2011) Global Rare Earth In-Use Stocks in NdFeB Permanent Magnets. Journal of Industrial Ecology. DOI: 10.1111/j.1530-9290.2011.00362.x.

444 ATIC (2020) Australian Critical Minerals Prospectus 2020. Department of Industry, Science, Energy and Resources, Australia; USGS (2020) Mineral Commodity Summaries 2020.

445 Huleatt M (2019) Australian Resource Reviews: Rare Earth Elements 2019. Geoscience Australia, Australia. DOI: 10.11636/9781925848441; Arafura (2018) Nolans Project. Viewed 18 September 2020, <https://www.arultd.com/projects/nolans.html>.

446 Office of the Chief Economist (2019) Outlook for Select Critical Minerals in Australia. Department of Industry, Innovation and Science, Australia.

447 China Power (2020) Does China Pose a Threat to Global Rare Earth Supply Chains?. Viewed 7 January 2021, <https://chinapower.csis.org/china-rare-earths/>; Stratfor (2019) The Geopolitics of Rare Earth Elements. Viewed 15 January 2021, <https://worldview.stratfor.com/article/geopolitics-rare-earth-elements#:~:text=China%20still%20controls%20the%20vast%20majority%20of%20all,with%20more%20than%2098%20percent%20of%20global%20supply>.

448 Haque N et al. (2014) Rare Earth Elements: Overview of Mining, Mineralogy, Uses, Sustainability and Environmental Impact. Resources. DOI: 10.3390/resources3040614.

449 Pavel C et al. (2017) Substitution strategies for reducing the use of rare earths in wind turbines. Resources Policy. DOI: 10.1016/j.resourpol.2017.04.010.

450 Pavel C et al. (2017) Role of substitution in mitigating the supply pressure of rare earths in electric road transport applications. Sustainable Materials and Technologies. DOI: 10.1016/j.susmat.2017.01.003.

Silicon

Silicon is derived from silica (SiO_2) found in quartzite or silica sands and is the second most abundant element on earth. The commonly documented resources and production of silica sand and silicon relate to lower purity material suitable for high volume applications such as glassmaking and construction. In contrast, HPQ (i.e. >99% purity) is required for both solar PV semiconductor material (e.g. solar wafers and computer chips) and manufacturing components such as crucibles. These deposits are scarce and reporting on resources is limited.

Currently, HPQ can only be found in a handful of locations around the world. The market is dominated by Belgian owned Sibelco (Unimin Corp) operating in Spruce Pine (US) whose product IOTA® is the benchmark for HPQ products.[451] Another key producer, QUARTZ Corp, operates their mine in the same location and processes their material in Norway.[452] While potential deposits have been found around the world, they have rarely been commercially viable.[453] For instance, Chinese and inner Mongolian deposits have faced commercialisation barriers with respect to quality consistency and expertise in mining and processing techniques.[454]

High geographical concentration of current resources combined with growing demand from solar grade silicon and other high-tech products has meant that HPQ is becoming increasingly critical. Supply vulnerability also stems from the current concentration of downstream solar grade silicon production in China and shortages of dedicated high purity silicon for the solar industry which are already reported to be of concern.[455] In light of this, and with increasing levels of activity to date (as shown in Table 10), there is significant potential for Australia to develop an HPQ industry.

Titanium

Titanium is found in the titanium-oxide mineral sands ilmenite ($FeTiO_3$) and rutile (TiO_2). Global production for these mineral sands is in the order of 6,945 kt and 648 kt per year, respectively. To date, the dominant use of titanium bearing mineral sands has been the production of titanium dioxide pigments for use in paints, paper and plastics.[459]

Table 10: Current HPQ activity in Australia

Company	Current activity in Australia
UltraHPQ	Recently upgraded to 1.2 Mt of 99% pure silica in situ[456] and stated intention of becoming a top 3 supplier into the solar PV and semiconductor markets.[457]
Yilgarn	Owned by Sinoquartz Tech (Lianyungang) Co Ltd, has quartz resources in North Queensland. Seeking to build a vertically integrated HPQ supply chain, though its processing plant will be located in China.[458]
Creswick Quartz	Currently has ownership over a deposit suitable for solar grade silicon and semiconductor applications.
Lavablue	Holds a license over a quartz resource in Queensland.

451 Sibelco (2020) Quartz. Viewed 21 December 2020, <https://www.sibelco.com/materials/quartz/>; Haus R et al. (2012) Assessment of High Purity Quartz Resources. Gotze J and Mockel R (Eds.) Quartz: Deposits, Mineralogy and Analytics. Springer Geology, Germany. DOI: 10.1007/978-3-642-22161-3_2; Verdant Minerals (2013) Silica and High Purity Quartz: Industry and Product Background Briefing Note. Viewed 28 October 2020, <http://www.verdantminerals.com.au/sites/default/files/PDF's/Presentations/About%20Silica%203.pdf>.

452 Norsk Mineral (2020) The QUARTZ Corp. Viewed 21 December 2020, <https://www.nomin.no/the-quartz-corp/category876.html>; Haus R et al. (2012) Assessment of High Purity Quartz Resources. Gotze J and Mockel R (Eds.) Quartz: Deposits, Mineralogy and Analytics. Springer Geology, Germany. DOI: 10.1007/978-3-642-22161-3_2

453 For example, I-Minerals (Idaho US), Momentive Quartz Technologies (Ohio,US, Germany, China, and Japan), Nordic Mining (Norway), JSC Polar Quartz (Russia), Russian Quartz LLC/KGOK (Russia); Chinese deposits (Xinyi in Jiangsu, Fenyang in Anhui, Gongan in Hubei).

454 Zhou J and Yang X (2018) A Reflection on China's high purity quartz industry and its strategic development. Material Science & engineering International Journal DOI: 10.15406/mseij.2018.02.00074.

455 Ewing J and Clark D (2021) Lack of Tiny Parts Disrupts Auto Factories Worldwide. New York Times, January 13. Viewed 15 January 2021 <https://www.nytimes.com/2021/01/13/business/auto-factories-semiconductor-chips.html>; Chigondo F (2018) From Metallurgical-Grade to Solar-Grade Silicon: An Overview. Silicon 10(3), 789–798. DOI: 10.1007/s12633-016-9532-7.

456 JORC Measured and Indicated.

457 UltraHPQ (2020) High Purity Quartz Limited Secures JORC Resource Upgrade. Viewed 7 January 2021, <https://ultrahpq.com/2020/08/12/high-purity-quartz-limited-secures-jorc-resource-upgrade/>.

458 Yilgarn Minerals (2020) About Yilgarn. <http://www.yilgarnminerals.com.au/home/>.

459 USGS (2020) Mineral Commodity Summaries 2020.

The critical nature of titanium however stems from its growing use as a strategic metal for the defence and aerospace industries, combined with the majority of production being undertaken in China (40%), Japan (26%) and Russia (21%).[459] Titanium metal (or sponge) is commonly produced from rutile using the Kroll Process, an expensive energy and labour-intensive process with high barriers to entry, largely due to the downstream integration in manufacture of defence and aerospace products.[460] In 2019, global sponge production was in the order of 210 kt.

Australia has large titanium resources, with 165 Mt of ilmenite (24% of global EDR, the second largest share after China) and 33.6 Mt of rutile (65% of global EDR) as reported in 2019.[461] Note that despite the relatively abundant mineral sands resources, estimates suggest approximately 44% of ilmenite and 26% of rutile resources are unavailable for mining because they are typically located in coastal regions and are therefore subject to competing land uses.[462] There may however be opportunities to recover titanium as a co-product of vanadium in some magnetite deposits.

Australia produced an estimated 592 kt of ilmenite and 190 kt of rutile in 2019 and through Tronox (based in Kwinana), has the world's largest integrated titanium dioxide operation.[463] However, currently there is no active local manufacture of titanium metal.

Given the low titanium content in PEM electrolysers, a significant increase in their deployment to 2050 is unlikely to materially impact global titanium supply (although titanium demand could increase should vehicle OEMs continue using titanium over steel in fuel cell bipolar plates). In light of this, the potential for Australia to emerge as a producer of titanium metal is likely to be driven first and foremost by increasing demand from the defence and aerospace industry.

Lastly, although some reductions in overall content may be achieved, there is reduced risk that titanium will be removed from PEM electrolysers due to the fact that these systems produce oxygen ions and require use of corrosion resistant layers to protect electrolyser stack components.[464]

Vanadium

Vanadium is typically located alongside iron and titanium in magnetite deposits and primarily mined as a secondary product.[465] Global production of vanadium is in the order of 73 kt, with demand primarily driven by its use in the production of high value steel alloys in Europe, Japan, Russia and China.[466] In 2019, China (55%) and Russia (25%) served as the dominant vanadium producers.[466] Locally, despite reporting 6,019 kt of vanadium EDR (25% of global supply), Australia is not an active producer.[467] There are however, several prospective projects in various stages of development.[467]

There is some uncertainty regarding the projected growth in vanadium demand from the steel sector and therefore its underlying criticality. This is somewhat supported by its recent price volatility wherein prices peaked at a 10-year high in 2018 before correcting in 2019 when supply growth (15%) outpaced expected growth in demand (6%).[468] Based on modest forecast deployment of VRFBs, use of vanadium for energy storage is unlikely to materially impact the overarching demand curve.

460 Roskill (2020) Titanium Metal: Outlook to 2030, 10th edition. <https://roskill.com/market-report/titanium-metal/>.

461 Senior A et al. (2020) Australia's Identified Mineral Resources 2019. Department of Industry, Science, Energy and Resources, Australia.

462 Geoscience Australia (2020) Titanium. Viewed 18 September 2020, <https://www.ga.gov.au/education/classroom-resources/minerals-energy/australian-mineral-facts/titanium>.

463 Senior A et al. (2020) Australia's Identified Mineral Resources 2019. Department of Industry, Science, Energy and Resources, Australia; Tronox (n.d.) Products: Mineral Sands Operations Perth, Australia. Viewed 15 January 2021, <https://www.tronox.com/products/mineral-sands/operations/perth-australia/>.

464 Kumar S et al. (2019) Hydrogen production by PEM Water electrolysis- A review. Materials Science for Energy technologies. DOI: 10.1016/j.mset.2019.03.002.

465 ATIC (2020) Australian Critical Minerals Prospectus 2020. Department of Industry, Science, Energy and Resources, Australia.; Bushveld Minerals (n.d.) About Vanadium. <https://www.bushveldminerals.com/about-vanadium/>.

466 USGS (2020) Mineral Commodity Summaries 2020.

467 Summerfield D (2019) Australian Resource Reviews: Vanadium 2018. Geoscience Australia, Australia. DOI: 10.11636/9781925848274.

468 Cripps Z (2020) Vanadium market set to grow steadily in the 2020s. Viewed 7 January 2021, <https://www.globenewswire.com/news-release/2020/06/25/2053209/0/en/Roskill-Vanadium-market-set-to-grow-steadily-in-the-2020s.html>; Bushveld Minerals (2020) Vanadium Overview. Viewed 7 January 2020, <https://www.bushveldminerals.com/about-vanadium>.

Should demand for vanadium continue to increase in both the steel and battery sectors, Australia may be well placed to capture some market share. For instance, although previously operational, Atlantic Ltd's Windimurra Vanadium is currently on care and maintenance. However a definitive feasibility study over the mine was completed in 2020 and the company appears to be waiting for investment and/or for the market to recover before restarting operations.[469] Further, the Federal Government has recently awarded Major Project Status to two vanadium mining projects: Australian Vanadium (targeting 10.2 kt annually of vanadium pentoxide) and Saint Elmo Vanadium (targeting 20 kt annually of vanadium pentoxide).[470]

Minerals risk rating

The investment risk related to each of the shortlisted critical minerals was based on the above assessment. Each metal was assessed qualitatively using a scale from 1 (lowest) – 5 (highest). The risk weighting applied to each factor is set out in Table 11.

Table 11: Minerals risk rating

Investment risk for Australia	Weighting	Al	Cr	Co	Cu	C	Li	Mg	Mn	Ni	P	Pt	REE	Si	Ti	V
Resource	20%	1	3	3	1	4	1	2	1	3	4	4	1	4	2	2
Production	30%	3	5	4	2	4	1	2	2	2	4	5	5	5	4	5
Global competition	30%	4	5	4	4	5	3	4	3	3	5	5	4	2	5	4
Local sustainability	10%	2	1	1	1	1	2	1	1	2	1	1	4	1	2	1
Demand	10%	2	2	5	1	2	1	1	1	1	1	2	3	1	1	4
Average Risk Rating		2.7	3.9	3.6	2.2	3.8	1.7	2.4	1.9	2.4	3.7	4.1	3.6	3.1	3.4	3.6

469 Atlantic (2020) Windimurra Vanadium Project. Viewed 21 December 2020, <https://atlanticptyltd.com.au/projects/windimurra>.

470 Commonwealth of Australia (2020) Current Major Projects. Viewed 8 January 2021, <https://www.business.gov.au/Grants-and-Programs/Major-Project-Status/Current-Major-Projects>.

Appendix C
Consulted stakeholder groups

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Karl Bunney
Keith Barnard
Kun Yang
Laura Kuhar
Leon Prentice
Liming Zhu
Lyndsey Benson
Mark Hedley
Mark Staples
Michael Rae
Mike Collins
Nick Cutmore
Noel Duffy
Phil Fawell
Raj Gaire
Richard Yong
Rob Hough
Robbie McDonald
Sam Spinks
Sandra Occhipinti
Shiping Chen

Industry, government and universities

ACE-EV
Advanced Manufacturing Growth Centre (AMGC)
Arafura Resources
Association of Mining and Exploration Company (AMEC)
Augsburg University
Australian Nuclear Science and Technology Organisation (ANSTO)
Australian Renewable Energy Agency (ARENA)
Australian Silica Quartz Group (ASQG)
Australian Strategic Materials (ASM)
Australian Vanadium (VSUN Energy)
BHP
BlueScope
CleanCo
Cobalt Blue
Creswick Quartz
CWP Renewables
Deakin University
Department of Foreign Affairs and Trade (DFAT)
Department of Industry, Science, Energy and Resources (DISER)
Department of Jobs, Tourism, Science and Innovation (JTSI, WA)
Department of Mines, Industry Regulation and Safety (DMIRS, WA)
EcoGraf
Element 25
Energy Renaissance
Everledger
Future Battery Industries CRC (FBICRC)
Geoscience Australia
Glencore
Hastings
Heathgate
Hitachi Metals
HyperPower Technologies
Hyundai
Incitech Pivot
Innovative Manufacturing CRC (IMCRC)
Japan Oil, Gas and Metals National Corporation (JOGMEC)
LavaBlue
METS Ignited
Minerals Council of Australia (MCA)
Minerals Research Institute of Western Australia (MRIWA)
Mitsui
National Renewable Energy Laboratory (NREL, USA)
Neometals
Northern Minerals
Office of Minister for Mines & Petroleum, Energy, Industrial Relations
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SunDrive Solar
The Australian Trade and Investment Commission (Austrade)
Toyota
United States Geological Survey (USGS)
University of New South Wales (UNSW)
University of Queensland (UQ)
University of South Australia (UniSA)
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