


Sustainability Evaluation of Energy Storage Technologies

Report prepared by the Institute for Sustainable Futures for the Australian Council of Learned Academies

Institute for Sustainable Futures
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About the authors

The Institute for Sustainable Futures (ISF) is an interdisciplinary research and consulting organisation at the University of Technology Sydney. ISF has been setting global benchmarks since 1997 in helping governments, organisations, businesses and communities achieve change towards sustainable futures. We utilise a unique combination of skills and perspectives to offer long term sustainable solutions that protect and enhance the environment, human wellbeing and social equity.

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Executive Summary

Key findings

This study of key energy storage technologies - battery technologies, hydrogen, compressed air, pumped hydro and concentrated solar power with thermal energy storage - identified and evaluated a range of social and environmental impacts along the supply chain.

Lithium-ion batteries in particular are anticipated to have a high rate of deployment and have significant associated adverse impacts, including human rights and pollution impacts during mining, fire risk, and are a future waste management challenge owing to the lack of established recycling systems.

Current planning and decision-making influencing the deployment of energy storage technologies needs to acknowledge and manage these short and longer-term impacts as they pose a significant risk to the viability of the industry and could hinder the transition to a renewable energy system.

Considering the major research, development and investment in energy storage technologies, it is likely that those that will dominate the market in the coming decades are unlikely to be the same technologies that dominate the market currently. Our evaluation demonstrates the importance of assessing environmental and social impacts across the whole supply chain to mitigate potential adverse impacts ahead of the implementation of new technologies.

Sustainable supply chains

KEY CHALLENGE: The mining of raw materials for battery production (such as lithium, cobalt and graphite) has significant environmental and social impacts, such as poor working conditions and health impacts from the pollution of local environments. There is a paucity of data and a lack of stakeholder awareness around these environmental and social impacts at the front-end of the supply chain, exacerbated by the complexity of the supply chains.

OPPORTUNITY: As an early market for batteries, Australia has an opportunity to champion storage sustainable storage supply chains. Australia's expertise in mining can support international standards development and engaged consumers can demand that the major brands, that can influence brand action globally and act responsibly.

Best practice for battery safety

KEY CHALLENGE: There are safety risks during transport, installation, use and handling and processing at end-of-life for energy storage batteries. Current safety initiatives are happening in the right direction but at the wrong pace. Safety risks are being addressed through industry-led voluntary initiatives, including the development of installation guides, training, accreditation pathways, the establishment of a national energy storage register, as well as standards development. However, the level of industry and consumer awareness and engagement may be out of step with the rapid rate of deployment and technology development.

OPPORTUNITY: There is an opportunity to promote the development of a vibrant and world-leading industry that models a culture of safety and best practice in installation, maintenance, use and end-of-life management. Fostering stakeholder awareness and incentivising the industry to engage with safety guidelines, without creating barriers for the emerging market necessitates consistent government intervention.

Responsible end-of-life management

KEY CHALLENGE: Energy storage batteries present a future waste management challenge, but if managed strategically, are a resource recovery opportunity. In the absence of an economic driver or clear policy directives there is currently no certainty for industry to invest in local end-of-life solutions for recycling and reusing storage batteries.

OPPORTUNITY: Australia has an opportunity to develop a stewardship approach to ensure the sustainable management of batteries across the whole product lifecycle. There is a strong rationale to act now to engage all stakeholders in developing a viable approach and to drive timely investment in recycling infrastructure and technology. A further impetus to act now is to coordinate with the current safety initiatives that are targeting retailers and installers – these stakeholders are critical for supporting a sustainable product stewardship scheme.

Our evaluation demonstrates the importance of assessing environmental and social impacts across the whole supply chain to mitigate potential adverse impacts ahead of the implementation of new technologies.

Introduction

Energy storage technologies are considered important for future energy systems with large amounts of variable renewable generation to ensure energy system adequacy and security. However they often have high resource requirements with consequent environmental and social impacts that need to be appropriately managed to support the transition to a sustainable energy system.

This report presents findings from an evaluation of the possible environmental and social impacts associated with the anticipated rapid uptake of energy storage in Australia; it also provides an appraisal of the important mitigation and management strategies.

This research contributes to a broader study examining the range of opportunities and challenges presented by the uptake of energy storage in Australia's energy supply and use systems out to 2030 delivered to the Australian Council of Learned Academies (ACOLA).

Five key stationary energy storage technologies are reviewed: Battery technologies – i.e., the dominant lithium-ion chemistries, lead-acid, sodium-based chemistries and flow batteries; pumped hydro energy storage (PHES); compressed air energy storage (CAES); hydrogen energy storage; and, concentrated solar power with thermal energy storage (CSP TES).

A 'streamlined' life cycle approach was developed, providing a consistent impact assessment framework to evaluate the technologies. The framework defined six environmental impact criteria: lifecycle energy efficiency, lifecycle greenhouse gas emissions, supply-chain criticality, material intensity, recyclability and environmental health; and, two social impact criteria: human rights and health and safety. This was applied to identify and characterise the impacts along the supply chain and mitigation strategies for the targeted storage technologies. A high-level comparison is presented in the following Table A with important impact factors discussed below.

Table A: Overall impact assessment showing the order of impacts from high low.

This coding was adjusted to account for the maturity of the mitigation strategies (reproduced from Chapter 8)

High, Medium, Low

		Li-ion NMC	Li-ion LFP	Lead-based	Flow batteries	Sodium-ion	PHES	CAES	Hydrogen	CSP with TES
Environmental Impact	Lifetime energy efficiency	Low	Low	Medium	Medium	Medium	Low	Medium	Medium	Low
	Lifecycle GHG emissions	Low	Low	Medium	Medium	Medium	Low	High	Medium	Low
	Supply chain criticality	High	Medium	Low	Medium	Low	Low	Low	Medium	Medium
	Material intensity	Medium	Medium	Low	Medium	Low	Low	Low	Low	Low
	Recyclability	Medium	Medium	Low	Medium	Medium	Low	Low	Low	Low
	Environmental health	Medium	Medium	Medium	Low	Low	Medium	Low	Low	Low
Social Impact	Human rights	High	Medium	Low	Low	Low	Low	Low	Low	Low
	Health & safety	High	Medium	Medium	Low	Low	Low	Low	Medium	Low
	Overall	High	Medium	Medium	Low	Low	Low	Medium	Medium	Low

Key lifecycle impacts

Lifetime energy efficiency

Lifecycle energy efficiency is important because a high efficiency maintained over a long expected lifetime minimises technology uptake requirements and the associated impacts.

Lithium-ion batteries perform well with a high average round-trip-efficiency (~ 90 %) compared to for example lead-acid (~ 80 %) and flow batteries (~ 75 %). The expected lifetimes for lithium batteries are also slightly longer, but still short in comparison to bulk storage technologies.

PHES has the highest round-trip-efficiency (75–80 %) of high-volume bulk energy storage technologies, compered to CAES (40-55 %), and also has the longest lifetime of all technologies between 50 and 150 years. Hydrogen-to-power is not competitive (20 %).

Lifecycle greenhouse gas emissions

Supply chain criticality not only considers geological availability of key resources but also potential supply chain vulnerabilities and risks associated with economic, technological, social or geopolitical factors; it provides vital insight for understanding technology development trends and enabling new opportunities for industry and research. Lithium-ion batteries have the highest level of criticality owing to the use of cobalt, natural graphite, fluorspar, phosphate rock and lithium. Considering the different lithium-ion battery chemistries, the nickel manganese cobalt oxide (NMC) chemistry is considered to have a higher level of criticality owing to the supply risk of cobalt; 50% of world cobalt production is from the Democratic Republic of Congo (DRC) and the vast majority of the world's resources in the DRC and Zambia. The security of supply of antimony used in certain lead-acid batteries and vanadium for Vanadium Redox Flow batteries (VRB) are also potentially of concern. Polymer Exchange Membrane (PEM) electrolysis technology for hydrogen production uses platinum catalysts that are identified as critical on the basis of supply chain constraints. For CSP TES plants, there are no issues in terms of material criticality of the TES materials (nitrate salts) although there are potential constraints on supply of silver and cerium for CSP. None of the materials used for PHES or CAES are considered critical.

Supply chain criticality

While the carbon intensity of the energy mix in the use phase has the biggest impact on lifecycle greenhouse gas emissions, as the system transitions to a renewable energy system the contribution to emissions of material extraction and manufacturing become more significant.

Considering the current high carbon-intensity of Australia's energy grid, in general the technologies with a high round-trip-efficiency, such as lithium-ion perform relatively well. For bulk energy storage, PHES likely performs the best whilst CAES is not competitive as it is typically integrated with natural gas combustion resulting in CO_2 emissions. Hydrogen-to-power is not competitive however the flexibility of hydrogen in terms of end-use could support the decarbonisation of heat, power, transport and industrial processes; there is also potential for large-scale long-distance renewable energy export. It is difficult to directly compare CSP with TES in terms lifecycle emissions because these systems generate electricity as well as provide energy storage, but within the system the thermal storage component contributes a very small amount to the overall emissions.

Material intensity

Owing to the high use of non-renewable resources in key energy storage technologies the material intensity is an important metric. In general, battery storage technologies have a higher material intensity compared to the other technologies. Lithium-ion batteries have a relatively high energy density that makes them less material intense than the alternative battery technologies (whilst noting there are significant differences between the lithium-ion chemistries). The material intensity of CSP is relatively high compared to other renewable generation technologies, however the molten nitrate salts used for thermal storage are abundant.

Recyclability

The recyclability of energy storage technologies has the potential to alleviate high material intensity through recycling, reuse, or remanufacturing.

Low recyclability highlights a need to develop new infrastructure and technology and stewardship approaches. Lead-acid batteries are the only battery technology to have a high level of recycling in Australia of 90% as recycling offers a return to recyclers and new batteries are typically manufactured with 60–80 % recycled content. Whilst most lithium-ion batteries are technically recyclable, at present, there is neither the economic driver nor a policy incentive for recycling in Australia. There are other niche resource efficiency pathways for batteries under development, for example the potential for 'rebirthing' batteries from electric vehicles at the end-of-first-life for use in stationary energy storage.

For hydrogen storage, there are established pathways (although not located in Australia) for platinum catalyst recycling capable of achieving high recovery efficiencies (greater than 95 %). Recycling is well established for the major materials used for PHES, CAES and CSP with TES; furthermore, the long lifetimes for these bulk storage technologies make the recyclability less vital.

Environmental health

Environmental health is important as adverse impacts to ecosystems or human health along the supply chain can undermine the benefits of moving to a renewable energy system. As batteries are material intense technology they have the most significant impacts. The impact varies depending on the location of mining, processing, and end-of-life, owing to differences in technology, production pathways and local environmental and social standards. The most significant impacts from mining in China include contamination of air, water and soil from lead, graphite and phosphate mining, all of which have serious health impacts.

Pumped Hydro
has up to
80%
round-trip-efficiency
and long lifetimes

50%
of world's cobalt
produced in Democratic
Republic of Congo

The cobalt mining area of the DRC is one of the top ten most polluted places in the world due to heavy metal contamination of air, water and soil, leading to severe health impacts for miners and surrounding communities.

Considering bulk storage technologies, whilst PHES has a relatively large land and infrastructure footprint the impacts can be minimised by locating in areas that have already been modified such as existing reservoirs, away from conservation areas and with closed loop systems that reuse water. CAES has a lower visible impact on landscape however the process of forming salt caverns for compressed air storage involves the removal and processing of large volumes of salt water. Hydrogen storage has a relatively low land-footprint (for electrolysis technology) and there is good potential to use existing infrastructure. Because water is a feedstock this is an important consideration in dry areas.

Human rights

There are significant human rights impacts associated with the material demand for lithium-ion batteries, particularly lithium and cobalt. The mining of cobalt in the DRC is often done by artisanal and small-scale miners who work in dangerous conditions in hand-dug mines without proper safety equipment and there is extensive child labour.

Whilst there is a significant paucity of published research on the impacts of lithium mining, investigations by journalists and NGOs highlight water-related conflicts and concerns over lack of adequate compensation for the local communities with many people remaining in poverty despite decades of lithium mining in Chile, and recently in Argentina. For the bulk storage technologies, there are potential conflicts over land use in Australia that could arise from new PHES, CAES or CSP TES development and mitigation strategies should consider the economic, social and cultural impacts of developments to local communities.

Health and safety

The inadequate management of health and safety risks potentially jeopardises the viability of the emerging stationary battery industry and highlights a need to engage all relevant stakeholders to adhere to best safety-practice. The potential for thermal runaway leading to fire and explosion is

considered a very significant safety issue for the dominant lithium-ion chemistries (e.g. lithium nickel manganese cobalt oxide) and has received a lot of public attention in the context of the recall of Samsung Galaxy Note 7 smartphones. That said, the fire risks are well known and can be mitigated by design modification, appropriate installation, monitoring and management systems, as well as adherence to safety protocols at end-of-life. Because these risks potentially impacts a broad range of stakeholders from manufacturers, transport workers, retailers, installers, consumers, emergency response teams and recyclers it is a challenge to engage all actors.

Owing to the relative immaturity of the industry significant focus has been directed toward ensuring safe installation with key initiatives including the development of installation guides and Standards Australia is expected to publish a new installation standard. Other future initiatives under consideration include establishing a national energy storage register, adopting international product standards and accreditation of installers. Current observance of these best-practice guidelines is on a voluntary basis.

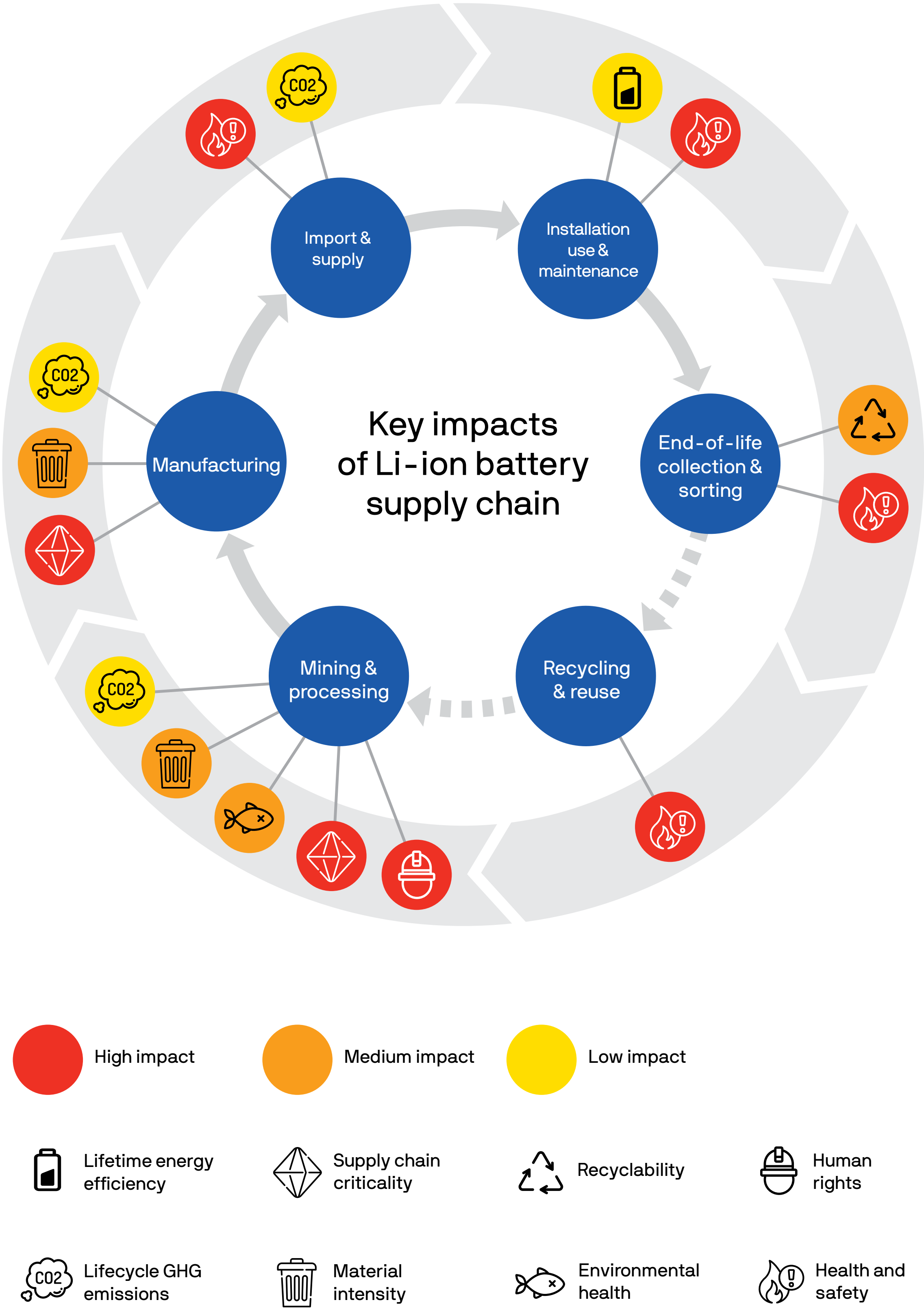
For hydrogen storage, the high flammability and mobility of H_2 molecules that can penetrate and damage internal structures, or lead to hard-to-detect leaks, present the main potential health and safety impacts; however, in the context of the likely near-term applications there are well-established management and mitigation strategies. Similarly, no high-order safety impacts are identified for PHES, CAES and CSP TES, all of which use mature technologies that are typically operated by trained workers. Workplace occupational health and safety measures are the main management strategies and the development of new policy to mitigate safety issues is not a priority.

ONLY
3-5%
of lithium-ion batteries sold onto the Australia market are collected for recycling

UP TO
80%
recycled content in lead-acid batteries

MORE THAN
95%
of platinum used as catalyst for hydrogen

Li-ion battery impacts



Priority interventions

It is clear that the lithium-ion battery technologies should be a priority as they present the highest-order environmental and social impacts and are likely to have high deployment and exposure to a range of stakeholders.

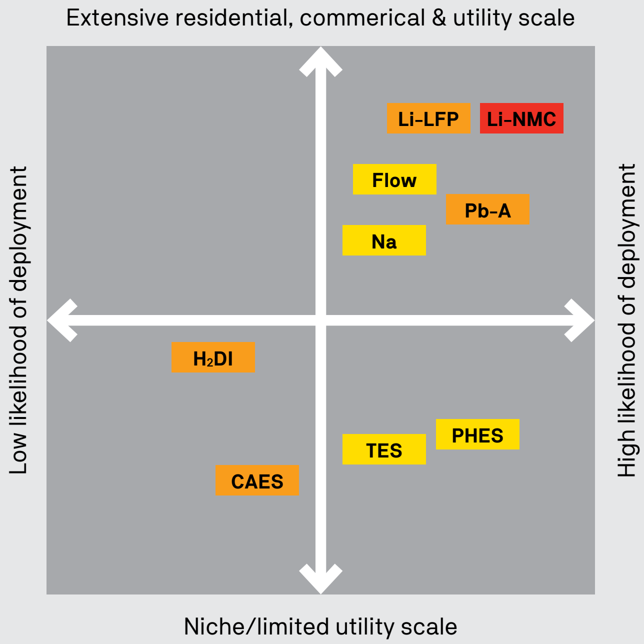
To evaluate the relative impacts and justify a priority focus for mitigation and management the overall risk and likely exposure ratings for the different technologies are located in a quadrant diagram (Figure A).

The colour of the box aligns with an overall risk rating based on the impact assessment framework (Table A). The vertical axis provides a range of likely deployments and is a proxy for level of exposure (i.e. more stakeholders are exposed for technologies deployed in residential and small commercial markets); the horizontal axis provides a range of in terms of likelihood of deployment consistent with the scenario modelling and techno-economics in WP1 and is a proxy for frequency. Those technologies clustered towards the top-right quadrant represent the greatest risk and justify a priority focus for mitigation and management.

On this basis, the priority focus for intervention is strategies that aim to mitigate the environmental and social impacts outlined above, namely:

1. Encourage the development of sustainable supply chains for metals
2. Engage the emerging battery energy storage industry actors to adhere to best safety-practice
3. Develop stewardship approaches for responsible management in use and at end-of-life

Figure A: Quadrant diagram showing relative risk and exposure ratings for the energy storage technologies (reproduced from Chapter 8)



Technologies

BATTERIES

Li-NMC	Lithium nickel manganese cobalt oxide
Li-LFP	Lithium iron phosphate
PB-A	Lead-acid batteries
Flow	Flow batteries
Na	Sodium-based batteries

BULK STORAGE

CAES	Compressed Air Energy Storage
H_2DI	Hydrogen Energy Storage (direct injection)
TES	Concentrated Solar Power with Thermal Energy Storage

1. Encourage the development of sustainable supply chains for metals

The front-end of the supply chain, particularly mining, material processing and manufacturing, has significant human rights and environmental health impacts. Most of these impacts occur outside of Australia, at different points along a complex supply chain. Furthermore, on the basis of expert stakeholder interview for this work it is apparent that they are not well known or understood by most stakeholders groups.

Australian governments and companies could take a leading role in putting sustainable supply chains on the global agenda by supporting key initiatives, including: ethical sourcing and Corporate Social Responsibility; mining and chain-of-custody standards, e.g. Australia has led the development of the Steel Stewardship Forum; national sustainable supply chain legislation; increased rates of recycling and reuse; and, new research to address the paucity of data characterising the supply chain impacts, criticality, and best approaches for mitigation.

2. Engage the emerging battery energy storage industry actors to adhere to best-practice for safety

The current focus of safety risk mitigation strategies prioritise installation, which makes sense in light of status of this emerging new industry for battery energy storage. The main initiatives are: the development of installation guides, the development of installation standards, efforts towards establishing a National Energy Storage Register, and efforts to align Australian initiatives with international product standards.

Presently, the key challenge is engaging with the industry to adopt best practice as standard development evolves. In the absence of any regulatory levers the Clean Energy Council has implemented ‘battery endorsement’ for PV accredited installers. Towards a more enduring (potentially regulatory) solution to encourage industry engagement and adherence to safety standards a number of industry stakeholders are advocating for changes to state and territory based electrical safety standards.

3. The development of stewardship approaches for responsible end-of-life management

Stationary storage batteries could present a significant waste management challenge or resource recovery opportunity in the coming decades. Thus, encouraging investment in end-of-life management infrastructure is an important priority as currently there is neither the economic or policy driver to incentivise investment.

To establish a product stewardship scheme there are multiple points of intervention along the supply chain (retail, installation, dis-installation, end-of-life) that highlights the need to engage a range of stakeholders. Expert stakeholder perspectives underlined the opportunity to align efforts to improve end-of-life management with complimentary ongoing efforts to ensure safety. This is because installation/dis-installation represents a shared critical leverage point for ensuring safety and establishing pathways for responsible end-of-life management; making the cost of end-of-life transparent at the point of sale (as opposed to the point of disposal) likely leads to better end-of-life management outcomes; and consistent approaches for stakeholder engagement and awareness raising is critical, e.g. protocols for information transmission along the supply chain with consistent signage and labelling. These viewpoints provide a strong rationale for action now rather than in ten years when the first installations reach end-of-life.

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ABBREVIATIONS

ACOLA	Australian Council of Learned Academies
ACT	Australian Capital Territory
AESDB	Australian Energy Storage Database
ARENA	Australian Renewable Energy Agency
AS/NZS	Australian/New Zealand standards
BEV	Battery electric vehicle
CAES	Compressed Air Energy Storage
CEC	Clean Energy Council
CEFC	Clean Energy Finance Corporation
COAG	Council of Australian Governments
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSP	Concentrating Solar Power
EU	European Union
EV	Electric vehicle
EWG	Expert Working Group
GHG	Greenhouse gas
GWh	Gigawatt hour
ICT	Information and communications technology
IRENA	International Renewable Energy Agency
LCA	Life Cycle Analysis
LFP	Lithium iron phosphate
Li-ion	Lithium ion
MW	Mega Watt
MWh	Mega Watt hour
NaS	Sodium-sulphur
NiCd	Nickel cadmium
NiMh	Nickel metal hydride
NiZn	Nickel Zinc

NMC	Lithium nickel manganese cobalt oxide
NSW	New South Wales
NT	Northern Territory
OCS	Office of the Chief Scientist
PHES	Pumped-hydro energy storage
PHEV	Plug-in hybrid electric vehicle
PV	Photovoltaic
QLD	Queensland
RET	Renewable Energy Target
SA	South Australia
TAS	Tasmania
TWh	Terrawatt hours
US	United States
VIC	Victoria
VPP	Virtual power plant
VRB	Vanadium redox flow battery
WA	Western Australia
ZnBr	Zinc Bromine

1 Introduction

1.1 Background

Australia's Chief Scientist, Dr Alan Finkel, has asked the Australian Council of Learned Academies (ACOLA) to develop and deliver a report on the opportunities from, and challenges to, the rapid uptake and widespread use of energy storage in Australia's energy supply and use systems. The project is delivered as a partnership between the Office of the Chief Scientist (OCS) and ACOLA.

The project considers the transformative role that energy storage may play in Australia's energy systems, identifies future economic opportunities and challenges, and describes the current state of and future trends in energy storage technologies. It examines the scientific, technological, economic and social aspects of the role that energy storage can play in Australia's transition to a low-carbon economy over the coming decade and beyond. While acknowledging the diverse applications and services that energy storage technologies can supply, this project focuses on storing significant volumes of low-carbon energy for electricity supply and transport in Australia, as well as research and export opportunities.

The project comprises two parts, **Phase I**, a report outlining current energy storage and **Phase II**, a collection of discrete work programs that investigate key aspects of the market identified in **Phase I**. More specifically, **Phase I** contains an overview of a broad range of available and emerging energy storage technologies and the diverse applications and services they can provide. It contains:

- a review of existing and emerging energy storage technologies,
- an overview of the diverse applications of energy storage technologies in the electricity and transport sectors
- a discussion of the Australian context for energy storage, including an overview of relevant policy and regulatory developments.

Phase II of the project investigates different uptake scenarios for energy storage technologies that can store significant volumes of low-carbon energy for electricity supply and transport in Australia. The project will identify Australia's research and industry strengths and weaknesses, and assess opportunities for Australia to participate in the energy storage supply chain. It will analyse the economic, social and environmental challenges of significant energy storage uptake in Australia and discuss the policy and regulatory implications Subject to final approval by the Expert Working Group (EWG) and OCS, Phase II is expected to include and identify:

- a multiple-scenario approach to identify the opportunities and challenges that energy storage presents in Australia (Work Package 1, WP1)
- the opportunities for Australian research and industry in the global and local energy storage supply chains, including domestic and export opportunities in manufacturing, software, instruments, knowledge, services and resources (Work Package 2, WP2)
- the cradle-to-grave environmental and safety benefits and risks presented by uptake of energy storage (**Work Package 3, WP3—this report**)
- the social drivers and barriers of energy storage uptake, and the potential benefit or detriment to the public in achieving energy storage uptake targets (Work Package 4, WP4)
- how policy and regulatory settings can help to realise the opportunities and benefits of energy storage uptake, and overcome the challenges and potential negative impacts identified over the course of the project (All Work Packages).

1.2 Project objectives and scope

This report presents findings from **Work Package 3**. The overarching objective of this work package is to characterise and evaluate environmental and social impacts and benefits, and to appraise the mitigation and management strategies.

The environmental benefits of low-carbon technologies in a future renewable energy system have been established with positive benefits for climate mitigation and reducing pollution. However, it is important to assess the full lifecycle of any new technology in order to minimise potential adverse impacts that may arise, and to make sure new environmental and social impacts are not created elsewhere. Renewable energy technologies typically have higher material requirements than fossil fuel technologies, but the emissions associated with this material intensity are small compared with the large impact from fossil fuel-fired power plants over their lifetime (Hertwich et al. 2014). Energy storage technologies are considered essential to future renewable energy systems, but they often have high resource requirements and potentially significant environmental and social impacts that need to be appropriately managed in order to realise a sustainable energy system.

Consistent with Phase I, and the scenarios developed for WP1, five key stationary energy storage technology groups are reviewed:

- battery technologies: lithium-ion, lead-acid, sodium-based chemistries and flow batteries
- pumped hydro energy storage (PHES)
- compressed air energy storage (CAES)
- hydrogen energy storage
- concentrated solar power with thermal energy storage (CSP TES).

Following this introduction, **Chapter 2** describes the research methodology and the environmental and social impacts considered in developing the impact assessment framework. The environmental impacts included are: lifecycle energy efficiency, lifecycle greenhouse gas emissions, supply chain criticality, material intensity, recyclability and environmental health. The social impacts are related to human rights and health and safety.

In Chapters 3–7, the impact assessment framework is applied to evaluate the five stationary energy storage technology groups: **Chapter 3** (Battery technologies), **Chapter 4** (PHES), **Chapter 5** (CAES), **Chapter 6** (Hydrogen) and **Chapter 7** (CSP TES). The impact assessment by technology considers the key impact factors and the maturity of the mitigation and management strategies. This is done to establish a high-level impact order that is rated from high to medium to low.

Chapter 8 provides a synthesis which compares the impact assessments across the different technologies to inform a discussion on priority policy interventions. This chapter evaluates the impact level and considers the likelihood and frequency of stakeholder exposure along the supply chain in alignment with the scenarios developed for WP1. This enables a prioritisation of key interventions to mitigate and manage impacts. The chapter concludes with a numbered list of key findings.

2 Methodology

2.1 Conceptual framework: lifecycle approach for environmental and social impacts

We have developed a streamlined lifecycle approach to identify environmental and social impact 'hotspots' along the supply chain after Ellingsen et al. (2016). The impact assessment framework consists of key criterion drawing on elements of environmental and social lifecycle assessment, as well as additional criteria that are crucial to the sustainability of stationary energy storage technologies, e.g., 'lifecycle energy efficiency', 'supply chain criticality' and 'recyclability'. The criteria are defined according to the environmental and social and safety impact categories given in Table 1.

The framework is intentionally broad to enable a comparison of the diversity of energy storage technologies, which are at varying levels of technological maturity. We have looked at impacts along the entire supply chain, including mining and material processing, manufacturing (of components and products), use (including transport, distribution and installation) and end-of-life. Rather than quantifying the impacts, these are highlighted as impact 'hotspots' for which further research or intervention is required. A detailed techo-economic assessment is outside of the scope of this study.

Table 1: Impact assessment framework

	Impact category	Definition	Importance
Environmental impact	Lifetime energy efficiency	Energy efficiency giving consideration to important statistics including round-trip-efficiency and expected lifetime	High energy efficiency maintained over a long expected lifetime equates to a low-order impact with the important outcome of minimising technology uptake requirements and associated impacts
	Lifecycle GHG emissions	The greenhouse gas emissions from the full lifecycle of a technology (differentiating between cradle-to-gate and cradle-to-grave)	A low-order impact for lifecycle emissions correlates with a competitive round-trip efficiency because, with the current high emission-intensity of the energy mix, the use-phase emissions typically contribute the largest amount to the overall lifecycle GHG emissions; the relative dominance of emissions associated with manufacturing and decommissioning increases with the transition to a low-carbon energy system
	Supply chain criticality	Criticality is a measure of the security of the material resources' supply chain. It considers a range of factors contributing to possible supply restrictions (importance, substitutability, susceptibility) and supply risks (geological, technological and economic, geopolitical, social and regulatory)	High-order supply-chain criticality recognises the potential for supply vulnerabilities with implications for future technology trends; Whilst criticality is not static and is nation-specific, understanding criticality provides important insights which open up new opportunities for industry and research.
	Material intensity	The use of non-renewable resources associated with material production, processing and use	High-order material intensity impacts, and the associated environmental and social issues, undermine the potential benefits of the transition to a low-carbon renewable energy system

	Impact category	Definition	Importance
	Recyclability	Recyclability includes recycling (whereby materials are returned to raw material production processes) as well as other material efficiency strategies, including product life-extension, reuse and remanufacturing. These pathways are influenced by material recovery value and maturity of recycling technology/infrastructure	High recyclability equates to a low-order impact, offering the potential to offset material intensity; a high-order recyclability impact rating highlights a need to plan for recycling infrastructure and technology development and/or alternative technology or system design to improve material efficiency.
	Environmental health	The potential damage to ecosystems and human health across the whole supply chain focusing on local impacts, e.g. air, land, water pollution and biodiversity	High-order environmental health impacts can undermine potential benefits of the transition to a low-carbon renewable energy system
Social impact	Human rights	For the local community and broader society this includes secure and healthy living conditions, access to resources and indigenous rights; for workers this includes fair salary, no forced labour, no child labour and safe working conditions	A high-order human rights impact due to poor respect for human rights poses a significant risk to the viability of the emerging industry (with implications for technology development and uptake trends); it highlights a need for harmonised global efforts and initiatives and brand leadership and recognition to champion better conditions
	Health and safety	Exposure to risks and hazards including fire, explosion and toxicity, considering which stakeholders are exposed and the frequency of exposure	High-order health and safety issues equate to significant risk factors impacting many stakeholders and without established mitigation strategies; it presents a risk to the viability of the emerging industry with implications for technology development and uptake trends, and highlights a need to engage all relevant stakeholders to adhere to best safe practice

Lifecycle assessment (LCA) is an established approach developed and applied to comprehensively assess a product/technology to quantify the environmental impacts associated with its whole lifecycle. Lifecycle sustainability assessment (LCSA) is a more recent approach that integrates environmental LCA with social LCA and lifecycle costing to consider environmental, social and economic impacts (UNEP 2011b). In light of the broad scope of this review of stationary energy storage technologies, and owing to differing levels of quality in data for the technologies that are at different levels of technical maturity, the application of the LCA methodology was not considered appropriate. However, a streamlined LCA method is used as a scoping method to provide early guidance for sustainable technology deployment (Ellingsen et al. 2016).

To inform the development of the impact assessment framework, supply chain management (SCM) and supply chain risk management (SCRM) approaches were reviewed. These approaches are concerned with the risk to companies, including financial, operational and reputational risks (Narasimham 2009). The application of these approaches is limited, as the links to natural resource use are very often ignored, and they do not consider the risks to other stakeholders, such as consumers, local communities or society (Matopoulos et al 2015). We have instead adopted a ‘criticality’ approach to address supply chain risks. This approach is discussed in more detail below.

There is a range of corporate social responsibility reporting and commitment initiatives for environmental, social and human rights, including the Global Reporting Initiative (GRI), the UN Global Compact and the Carbon Disclosure Project (CDP). The Global e-Sustainability Initiative (GeSI) has developed a sustainability assessment framework for the electronics industry. However, none of these frameworks were considered appropriate for this analysis as they do not address all the relevant impacts of stationary energy storage technologies, e.g. energy efficiency and recyclability.

Thus, for this analysis we have developed a framework based on streamlined LCA methods. It draws on the supply chain risk management and corporate social responsibility literature, and on technical criteria characterising the storage technologies. These aspects have been combined to address the environmental and social impacts. We have chosen this approach because: SCRM is not a system-wide approach, LCA considers the system but is product specific, and existing CSR frameworks are not appropriate.

2.1.1 Environmental impacts

As we are not attempting to quantify the environmental impacts, but identify key 'hotspots' across the supply chain, a traditional environmental life cycle assessment (E-LCA) was not considered appropriate. We also have a strong emphasis on qualitative impacts in our assessment. For example, where an E-LCA may have a value for water use or human toxicity, this does not give qualitative information that is very location specific, such as the impact of water use on the environment and/or the human health effects occurring at mining regions that we are interested in assessing.

LCA considers final impacts to human health, resource depletion and ecosystem quality, with midpoint impacts including climate change, land and water use, human toxicity and environmental pollution (UNEP 2011b). In the framework developed for this work, resource depletion is considered in the impact categories of **material intensity** and **recyclability**. Climate change impact is considered in the category of **lifecycle GHG emissions**. Our **environmental health** impact category appraises damage to ecosystems and human health, including typical LCA criteria of land use, water use, human toxic effects, biodiversity and other pollutants.

We have included technical characteristics that are of high relevance and they should be considered as standalone impact categories due to their high impact on the sustainability of technologies, particularly **lifetime energy efficiency** and **recyclability**. The **supply chain criticality** category is both an environmental and economic impact, owing to the economic impacts associated with vulnerability to shortages of raw materials. As these impact categories are additional to the scope of a LCA, further definitions are given below.

Lifecycle Energy efficiency: Acknowledging the range storage technologies and possible applications, there are a number of ways to measure efficiency. Because different efficiency measures vary in their importance depending on the application of the technology, it is important not to rely on a single measure. For example, for long-duration storage (i.e. weeks or months) the self-discharge rate (i.e. how quickly a storage device loses its stored energy when not in use) is very important. For efficiency when in use, the round-trip efficiency, a measure of the ratio of the energy retrieved from the battery to the energy put into the system, is an important statistic. This is because a higher round-trip-efficiency reduces the technology uptake requirement and emissions. However, it is also important to consider the expected lifetime of a storage technology as this factor, coupled with round-trip-efficiency, determines the total energy that can be stored and released over the lifetime, with implications for minimising total resource requirements and associated impacts. Thus, in this review we consider round-trip efficiency as well as other statistics. For example, in the case of batteries, the cycle-life is defined as the number of complete charge-and-discharge cycles the battery can perform before its storage capacity diminishes to 80 %.

Recyclability: The concept of recyclability, includes: 'recycling' where a material in a product at the end-of-life is returned to a raw material processing processes; 'reuse' occurs when a product at the end-of-life is reused in a different (lower order) application; and, 're-manufacturing' occurs when a product at end-of-life is remanufactured so it is of equivalent performance to a new product.

The amount of recycling of materials can be measured by the recycled content (the portion of secondary material input into total material input for production) or the end-of-life recycling rate (the portion of a material recycled at end-of-life, an indicator of recycling effectiveness, including collection, sorting and recycling technologies) (UNEP 2011a).

In this framework, recycled content is reflected in reduced material intensity. For recyclability, we consider the end-of-life recycling rate of products, their current technical recycling potential and their material value for recycling.

Criticality: The concept of material 'criticality' can be measured in various ways. Graedel et al. (2015) have developed a measure of criticality based on three pillars: supply risk (geological, technological and economic, geopolitical, social and regulatory) a country's vulnerability to supply restrictions (importance, substitutability, susceptibility) and environmental implications. The European Commission (2014c) criticality measure is based on economic importance and supply risk defined according to substitutability, end-of-life recycling rate, and the proportion of producing countries that have poor governance. Criticality is dynamic over time in response to changes in technology and geopolitics. The degree of criticality is not static between corporations or nations, but varies depending on who it is assessed for (Ciacci et al. 2016a).

Aside from quantitative measures of criticality, we have also reviewed qualitative aspects of the supply chain, including the major uses of materials and what potential impact this could have on supply for energy storage technologies. For example, lithium-ion batteries are the main end-use for cobalt, so changes to the supply of cobalt will have a large influence on the industry. But the inverse also needs to be considered. For example, batteries are only a small market share for the use of phosphate rock, of which 95% is used in agriculture, so small uses such as battery manufacturing may be de-prioritised in the case of supply chain disruptions. Where information exists, we have included the major countries and corporations involved and their share of the global supply chain.

2.1.2 Social impacts

As with environmental impacts, we have drawn on aspects of Social Life Cycle Assessment (S-LCA) to determine the main criteria for this analysis. The main impact categories of a S-LCA have been simplified to focus on the categories of **human rights** and **health and safety**. The main stakeholder groups considered are workers, consumers and local community, and we have also considered value chain actors and society as a whole where appropriate (Benoît & Mazijn 2009).

The **human rights** category considers impacts that would normally fall under categories of working conditions, cultural heritage, governance and socio-economic repercussion, and is focused on **workers** and the **local community** as the main stakeholder groups. The sub-categories we have included are in line with S-LCA guidelines. For **workers**, the main issues included are around child labour, fair salary, working hours, forced labour, equal opportunities/discrimination, and social benefits/security. For the **local communities,** we have focused on access to resources, cultural heritage, safe and healthy living conditions, respect for indigenous rights, community engagement, local employment and secure living conditions.

For the category of **health and safety**, we have focused on impacts for **workers** along the supply chain (particularly in manufacturing, installation, maintenance and end-of-life) and **consumers**. Health and safety impacts during the mining phase are addressed in the human rights criteria, as they relate to broader issues of including working conditions and child labour that include safety impacts.

There are some impacts discussed in the environmental impacts criteria that also cross over with social impacts, but have only been included once to avoid duplication. The environmental health category includes health impacts on workers and communities, for example those arising from the contamination of heavy metals during mining. We have chosen to discuss these in the environmental health category, as they are impacts primarily arising from changes to the environment, and the consideration of human toxic effects is also within the scope of on an E-LCA.

2.2 Method

The evaluation of the 'order' (high-to-medium-to-low) of the environmental and social impacts was based on an integrated approach informed by a comprehensive literature review, expert stakeholder interviews and an appraisal of the maturity of the mitigation and management strategies.

2.2.1 Literature research

To determine the impacts arising in our framework we carried out a comprehensive literature review. This included a review of academic literature from scientific journals in a range of disciplines including environmental and social lifecycle assessments, supply chain analyses, environmental toxicology studies and social research. Research and consulting reports commissioned by Australian and international governments and other organisations were also reviewed, along with relevant policy documents, legislation and guidelines. Owing to the rapid technological developments in energy storage and the significant lack of published research on some aspects (e.g. the effects lithium mining), grey literature including news reports, NGO reports, and company websites was also reviewed.

2.2.2 Expert interviews

Interviews were undertaken with a mix of stakeholders, including government representatives, academics, not-for-profit organisations and industry (including energy utilities, manufacturers, retailers, and recyclers).

Category	No of interviewees	Breakdown
Government	4	Two from federal government and two from state government
Industry	6	Two recyclers, two utilities, one manufacturer and one retailer
Organisation	5	Two energy, two recycling and one environmental organisation
Academics	5	Three experts on technology development (batteries, CSP and hydrogen), one on material criticality and one on recycling. Two of these are international.

Interviews were undertaken in a semi-structured format with open-ended questions that were tailored to the knowledge area of the interviewee. Key objectives of undertaking semi-structured interviews with stakeholders included:

- eliciting **stakeholder knowledge and perceptions** of environmental and social impacts influencing their own organisation or sector and filling gaps in the literature where information is either out-of-date or not available
- understanding the **supply chain** (to inform both understanding and location of impacts, and potential interventions), as much of this information is not published
- understanding stakeholder **priority intervention points** (along the supply chain) to mitigate impacts
- **validating the impact assessment framework** to make sure it adequately considers the full scope of environmental and social impacts.

In our analysis, interview responses were primarily used to understand the current status of strategies used to mitigate potential impacts, and identify key priority interventions going forward.

2.2.3 Maturity of mitigation strategies

An impact level for each impact category is developed from high to medium to low according to the key below:

The degree of impact for each technology was based on the literature review and expert stakeholder interviews, as well as characterisiation of the 'maturity' of the strategies for mitigation and management of the potential impacts. We have categorised the maturity for each strategy as being one of the following:

- *Immature* – e.g. R&D agenda, absence of policy/ incentive
- *Maturing* – e.g. mitigation technology exists but not deployed at scale
- *Mature* – e.g. well-established mitigation strategies demonstrated in industrial context

This maturity affects the overall ranking of the impact. For example, a potential high-level impact may be identified for a technology, but if there is an established mitigation strategy in place that is considered 'mature' then the final impact level is calibrated appropriately.

3 Energy storage batteries

3.1 Introduction

Battery storage technologies are undergoing rapid change and their uptake is expected to be significant. However, they have a range of environmental and social impacts along their supply chains that need to be considered. To review these impacts, we have focused on four main technologies: lead-acid batteries, lithium-ion batteries, flow batteries and sodium-based batteries. Technologies are included according to their technical maturity, the maturity of the supply chain, and recent deployments – consistent with previous studies (Cavanagh, Behrens, et al. 2015; Cavanagh, Ward, et al. 2015) and the *Phase I* research preceding this study (Banfield & Rayner 2016).

When comparing battery technologies, it is important to consider that while they have many commonalities, their functions and future applicability for energy storage are not identical due to differences such as chemistry, size and weight. In particular, different grid services are associated with different durations and therefore they require different battery technologies. Presently, lithium-ion batteries are the only technology suitable for the short duration purposes owing to their energy-to-power ratio. Lithium-ion and lead-acid batteries are best suited for medium storage durations of less than one hour, whereas currently the most technically advanced sodium and flow batteries are more suitable for long duration applications of less than one day (Leadbetter & Swan 2012). We note that there is a major research and development effort focussed on advanced battery chemistries coupled with increasing investment in start-up battery technology companies; and thus, the technologies that may be dominant in the near term are unlikely to be the same technologies that dominate the market in 10–20 years. Whilst predicting a disruptive technology is outside the scope of this research, this evaluation approach could be applied for appraising new technologies to understand possible adverse impacts ahead of their implementation.

Lead-acid

Lead-acid batteries are currently the dominant battery technology despite comparatively low energy and power levels because of their low cost and high maturity level, but lithium-ion batteries are rapidly displacing them. There are two main types, flooded-cell batteries (that are common in the automotive industry) and sealed batteries. The latter is becoming more common for renewable energy storage applications as they are considered to be safer (Cavanagh, Ward, et al. 2015).

Lithium-ion

Lithium-ion batteries are highly desirable for energy storage because of their high energy and power output and high efficiency. The high costs that were preventing their wide-scale uptake have reduced significantly in the last few years. There are a large number of lithium-ion battery technologies under development and the chemistry of these influences their potential environmental and safety impacts. The major chemistries currently in production are based on a graphite anode with the different chemistries using a range of materials for the cathode. These include lithium nickel cobalt aluminium oxide (NCA), lithium nickel manganese cobalt oxide (NMC), lithium cobalt oxide (LCO), and lithium iron phosphate (LFP). Owing to their market share for stationary energy storage and electric vehicles our analysis focuses on NMC and LFP chemistries.

Flow batteries

This includes two categories, vanadium redox batteries (VRB) and zinc bromine batteries (ZnBr), both of which are mature technologies. The latter has been commercialised in Australia by Redflow. These technologies are considered safe compared to dominant lithium-ion based chemistries and are suitable for application where long-duration storage is required.

Sodium-based chemistries

This technology includes two categories for large-scale grid support as well as 'salt-water' (electrolyte) batteries. Sodium-sulphur (NaS) batteries have been deployed in Japan and USA. These batteries operate at elevated temperatures (> 300 °C) and have relatively long lifecycles. In Australia, sodium-nickel-chloride ($NaNiCl_2$) is under development for grid storage (Banfield & Rayner 2016). There is also significant investment in new sodium-ion chemistries specifically targeting residential and small commercial renewable energy storage applications (ARENA 2016). Salt-water chemistries already on the market are targeting niche applications, e.g. rural and regional energy storage. Sodium-nickel-chloride batteries use relatively stable and non-hazardous materials and are considered environmentally sound and safe. Aquion Energy is a leading developer in this category, and Aquion has developed the only battery technology to be cradle-to-cradle certified with a bronze rating (Aquion Energy n.d.).

A summary comparison of the environmental and social impacts of battery technologies is shown in Table 2, and each impact is then elaborated in the following sections.

Table 2: Impacts of major battery storage technologies

		Lithium-ion NMC	Lithium-ion LFP	Lead-acid	Flow	Sodium-based
Environmental impact	Lifetime energy efficiency	Round trip efficiency: High (compared to other batteries) Self-discharge: Good Lifespan: Long (~10 years) Cycle life: Long	Round trip efficiency: High (but lower than NMC) Self-discharge: Good Lifespan: Long (~10 years) Cycle life: Long	Round trip efficiency: Med (compared to other batteries) Self-discharge: Good Lifespan: Medium (~5-10 years) Cycle life: Short	Round trip efficiency: Low (compared to other batteries) Self-discharge: Good (negligible) Lifespan: Long (>10 years) Cycle life: Long	Round trip efficiency: Med (compared to other batteries) Self-discharge: Poor Lifespan: Medium (~8 years) Cycle life: Medium
	Lifecycle GHG emissions	Cradle to gate: Low ~25kgCO2e/MWh (mostly from Nickel and Cobalt) Use: Low (high round trip efficiency)	Cradle to gate: Low ~25kgCO2e/MWh (higher than NMC due to lower energy density) Use: Low (high round-trip efficiency)	Cradle to gate: High ~75 kgCO2e/MWh Use: Medium (medium round-trip efficiency)	Cradle to gate: Low ~20 kgCO2e/MWh Use: High (low round-trip efficiency)	Cradle to gate: Medium ~50 kgCO2e/MWh Use: Medium (medium round trip efficiency)
	Supply chain criticality	Critical: Natural graphite 65% of production in China, Fluorine 60% of production in China, Cobalt >50% of production in the DRC Near critical: Lithium	Critical: Natural graphite 65% of production in China, Fluorine 60% of production in China, Phosphate Rock 50% of production in China, 70% of reserves in Morocco/Western Sahara Near critical: Lithium	Non-critical: Lead Critical: Antimony (only in some types)	Near critical: Vanadium Non-critical: Bromine	Critical: Natural graphite 65% of production in China Non-critical: Sodium
	Material intensity	High material demand (lower than alternative Li-ion chemistries)	High material demand (higher than alternative lithium-ion chemistries)	High material demand but the production of new batteries includes 60% to 80% recycled content	Medium level of material demand	Lower material demand than alternative battery types
	Recyclability	High recycling potential Low material value for recycling, except for cobalt Potential to reuse EV batteries for storage	High recycling potential Low material value for recycling Potential to reuse EV batteries for storage	High recycling potential and high recycling rates (90% for Australia) High material value for recycling	High recycling potential Low material value for recycling Battery can be re-used with new electrolyte	High recycling potential Low material value for recycling
	Environmental health	China: Air pollution from graphite dust, leading to respiratory ailments; Water pollution from acids into local water sources including drinking water Lithium: Australia: large volumes of waste rock, high water use Argentina & Chile: Water pollution and depletion; leaching,	China: Air pollution from graphite dust, leading to respiratory ailments; Water pollution from acids into local water sources including drinking water Lithium: Australia: large volumes of waste rock, high water use	China: Heavy metal contamination of water, soil and plants with lead and cadmium; Serious human health impacts especially for children.	No major impact identified	China: Air pollution from graphite dust, leading to respiratory ailments; Water pollution from acids into local water sources including drinking water

		Lithium-ion NMC	Lithium-ion LFP	Lead-acid	Flow	Sodium-based
		spills or air emissions of chemicals Cobalt: Soil and water pollution leading to heavy metal contamination of communities	Argentina & Chile: Water pollution and depletion; leaching, spills or air emissions of chemicals Phosphate: China: large volumes of waste rock, contamination of water with uranium, arsenic and cadmium with human health impacts; Namibia: Potential risk for seabed mining			
Social impact	Human rights	Lithium: Chile and Argentina: Water related conflicts with communities Cobalt: DRC: Poor labour conditions, artisanal mining, child labour	Lithium: Chile and Argentina: Water related conflicts with communities	No major impact identified	No major impact identified	No major impact identified
	Health and safety	Use: Risk to consumers of fire due to thermal runaway, currently no regulated standards for installation Transport: Risk of fire in domestic and international transport (end-of-life) End-of-life: Risk to workers of fire in landfill and at recycling, which can shut down plant No consensus on how to extinguish Lack of data for first responders and recyclers.	Medium–low risk of fire, batteries designed to prevent thermal runaway	Potential emission of corrosive and potentially explosive mix of H_2 and O_2 during last stage of charging Sulphuric acid used as electrolyte can also cause burns if exposed	Non-hazardous materials and non-combustible	Non-hazardous materials and non-combustible

3.2 Environmental Impacts

3.2.1 Energy efficiency

There is no one way to measure and compare the energy efficiency of battery technologies; to appraise their efficiency, we consider both the efficiency of the battery in use and its expected lifetime.

The efficiency of the battery in use can be measured by its round-trip efficiency (or cycle efficiency), which is the ratio of energy retrieved from the battery to that put into the system. The self-discharge rate also affects efficiency, and is a measure of how quickly a battery will lose its stored energy when not in use. This loss is due to internal chemical reactions that reduce the stored charge, and is affected by the battery temperature.

The lifetime of the battery should also be considered, as this determines the total amount of energy than can be put into and taken out of the battery over its life. The lifetime of a battery can be measured by its calendar life, a measurement in years of the length of time that the battery is usable, regardless of whether it has been active or inactive. Cycle life is a measure defined as the number of complete charge-and-discharge cycles the battery can perform before its capacity falls to 80% of its initial capacity. A high cycle life allows for more energy throughput over the life of the battery. Cycle life is affected by the operating conditions of a battery. In most conditions, batteries will not be used so that they fully charge and discharge with each use; instead, they only partially charge and discharge. A shallower depth of discharge will increase the cycle life of battery, so should be considered when discussing cycle life (Battke et al. 2013).

Lithium-ion batteries perform well across all the above criteria, with a high average round-trip-efficiency of 90%, minimal self-discharge, and high cycle life and calendar life. Between the dominant lithium-ion chemistries, the NMC battery has a higher round-trip-efficiency than the LFP (Reuter 2016).

Lead-acid batteries have a lower round-trip-efficiency and calendar life compared to lithium-ion batteries, and are similar to sodium-based batteries in this regard. They perform well for self-discharge rate but poorly for cycle life. They have the shortest cycle life of all the battery technologies.

Flow batteries have the lowest round-trip-efficiency of all battery technologies in this study, but are the only batteries to have negligible self-discharge, which makes them preferable for applications where batteries may remain unused for extended periods of time. They perform the best in terms of cycle life and have a high calendar life.

Sodium-based batteries that are currently available on the market have an average round-trip-efficiency and calendar life, comparable to lead-acid, but a better cycle life, which makes them a potential replacement for lead-acid batteries in the market. They perform poorly on self-discharge rates.

A comparison of these battery types is given in Table 3.

Table 3: Energy efficiency characteristics of major battery technologies

	Lithium-ion	Lead-acid	Flow (VRB)	Sodium (Na/S)	Source
Round trip efficiency	80–98%	63–90%	75–80%	75–90%	Leadbetter & Swan, 2012
	Mean 90% Range 85–90%	Mean 82% Range 80–90%	Mean 75% Range 70–80%	Mean 81% 71–90%	Battke et al, 2013
Self-discharge per day	0.1–0.3%	<0.5%	Negligible	20%	Leadbetter & Swan, 2012
Calendar life (years)	Mean 11.5 Range 5–15	Mean 8.5 Range 5–15	Mean 9.5 Range 5–10	Mean 8.5 Range 5–15	Battke et al, 2013
Cycle life (number of cycles)	3000+ @ 80%	200 to 1800 @ 80%	12,000+ @ 100% >270,000 @ few %	4500 @ 80%, 2500 @ 100%	Leadbetter & Swan, 2012 (at % state-of-charge variation)
	Mean 10250 Range 1000–30,000	Mean 1250 Range 500–2000	Mean 13,000 Range 10,000–15,000	Mean 3333 Range 2500–5000	Battke et al, 2013 (at 80% depth-of-discahrge)

3.2.2 GHG emissions

In assessing the contribution of battery technologies to greenhouse gas emissions, we have reviewed the global warming potential (GWP) over the lifecycle. There are limited studies on the lifecycles of batteries for application in stationary energy storage (Hiremath et al. 2015), but there have been extensive assessments for their application in electric vehicles (Ellingsen et al. 2013; Amarakoon et al. 2013; Notter et al. 2010; Reuter 2016) and in general applications (Oliveira et al. 2015; Sullivan & Gaines 2012).

The use stage of batteries dominates their energy consumption across the lifecycle, and therefore also has the potential to be the most important consideration in terms of global warming potential depending on the energy mix used. However, if the electricity used in the grid is from renewable sources the GWP impact from material production and manufacturing (cradle-to-gate) becomes the most important consideration (Amarakoon et al., 2013; Oliveira et al, 2015). In this case, the proportion of renewable energy used in the manufacturing and use of batteries has a significant impact on their greenhouse impacts. In addition, the use of recycled materials, or the reuse of the batteries themselves, should be promoted to reduce their overall impact. Although batteries may be used in various applications and for different grid services, the relative GWP of different batteries is not significantly dependent on the particular stationary application (Hiremath et al., 2015).

MATERIAL PRODUCTION AND MANUFACTURING

The cradle-to-gate environmental impact of batteries is a useful measure as it evaluates the environmental impact of batteries to the point when they are ready for purchase, excluding their use and disposal at end-of-life. This includes two lifecycle stages of battery material production (the extraction or recycling of materials and their processing and refining so they are ready for manufacture) and battery manufacturing (including the manufacture of the components and the battery product).

Flow batteries (specifically the Vanadium Redox Flow chemistry) perform the best of the major battery technologies, with the lowest GWP per MWh of energy, closely followed by **lithium-ion**. **Sodium-sulphur batteries** have around twice the GWP of lithium-ion and flow batteries, and lead-acid have a significantly higher impact[1]. **Lead-acid batteries** that are manufactured with 60–80% of recycled content have the lowest impact in terms of GWP per kilogram of battery. That said the impact per kilogram might be a less useful measure than per MWh considering the range of energy densities of the different technologies that is discussed below (Hiremath et al., 2015, based on technology characteristics from Battke et al 2013).

Within **lithium-ion battery technologies,** a comparison of lifecycle impacts found that LFP batteries have higher cradle-to-gate GWP emissions than NMC batteries; this was mainly owing to the lower energy density which requires a higher battery mass (Reuter 2016).

The most effective way to reduce the cradle-to-gate GWP impact is to reduce the carbon intensity and consumption of electricity in the production process (Ellingsen et al. 2013). As discussed above, the use of recycled materials can also significantly reduce the energy and emissions from material production for batteries, as demonstrated in the case of lead-acid batteries where the use of recycled lead reduces their cradle-to-gate GWP by around 25% (Hiremath et al., 2015). While the use of recycled materials has an impact on the cradle-to-gate energy and emissions, the contribution to overall lifecycle is less significant owing to the large impact of the use stage of a battery lifecycle. There are other reasons to increase the recycling of batteries, including the conservation of resources and the minimisation of other adverse environmental emissions in material production (Sullivan & Gaines 2012).

USE

As the use phase dominates the lifecycle impacts of batteries, unless the electricity mix used to charge them has a high proportion of renewable energy, it is misleading to compare environmental performance only on the basis of cradle-to-gate impacts (Hiremath et al., 2015). The use phase has the potential to significantly affect the overall environmental performance of a battery when considering the entire lifecycle from cradle to grave, and the efficiency of the battery becomes the main determinant of performance (Oliveira et al. 2015).

Lithium-ion batteries have the lowest GWP impact in the use phase, followed by lead-acid and sodium-based batteries. Flow batteries have the highest impact, which offsets their low cradle-to-gate impact.

In considering the cradle-to-grave GWP impacts (not considering recycling), lithium-ion batteries perform significantly better than the other battery technologies. All the other technologies have similar levels of impact (Hiremath et al., 2015).

END OF LIFE

The impact of recycling on GWP on the battery lifecycle has not been compared across battery technologies owing to a lack of data. Studies have found that the recycling of cathode materials, particularly cobalt and nickel, is less GHG intensive than procuring virgin cathode materials (Dunn et al. 2015).

[1] An alternative study by Oliveira et al (2015) found sodium-based batteries to have the lowest GWP for manufacturing, but this was based on very high assumptions for cycle life compared to those given by Battke et al. 2013 and Leadbetter & Swan, 2012.

An alternative to recycling is the reuse of batteries from electric vehicles (EV) in stationary applications, which creates an environmental benefit. A recent study to assess the environmental impact assumed a battery could be used for eight years in an EV followed by re-manufacturing for (re)use for an additional ten years in stationary energy storage (Ahmadi et al. 2017).

The benefit of reusing batteries increases if the electricity used to recharge the battery is from renewable sources, as the impact from manufacturing becomes more significant in the lifecycle of a battery. However, if the electricity is from non-renewable sources it will reduce the positive impacts of reuse (assuming a relatively low round-trip-efficiency). Even with re-manufacturing, a battery will degrade over time and the round-trip-efficiency will decrease, directly impacting total electricity use and therefore emissions.

Extending the life of batteries through reuse will still require recycling, but this will be delayed, which has the potential to delay the development of recycling technologies or require additional mining of metals to satisfy demand in the interim.

MITIGATION STRATEGIES

In order to reduce the GWP impacts of batteries along the lifecycle, batteries should be chosen after considering their cradle-to-gate and use stage impacts. The best way to reduce impact is to focus on low-carbon electricity in the use phase, followed by manufacturing and incentivising material recycling.

Considering the high carbon intensity of Australia's energy grid, the choice of battery technologies for deployment for stationary energy storage should focus on those that have a high round-trip-efficiency, such as lithium-ion, until the proportion of renewable energy in the grid is increased.

3.2.3 Supply chain criticality

All types of batteries have materials in their supply chain that can be considered critical, which could result in supply disruptions or price spikes. **Lithium-ion batteries** have the highest level of criticality, particularly owing to the presence of graphite, lithium, cobalt, fluorspar and phosphorus. **Sodium-based batteries**, based on the composition of NaS, also use a small amount of graphite but their materials are otherwise not considered critical. Antimony, a metal used in certain types of lead-acid batteries, has the highest level of criticality across all materials assesse. However, **lead-acid batteries** are of less concern as the amount of antimony used has declined over time, and they are mainly composed of lead which is not considered critical and has high recycling rates. **Flow batteries** also need consideration, as vanadium, which is used in one of two main chemistries, is considered 'near-critical'.

A comparison of NMC and LFP batteries found that several raw materials have a supply risk that is considered critical according to the European Commission methodology (Reuter 2016). Natural graphite and fluoride are critical for both, as well as phosphate for LFP batteries and cobalt for NMC. When the criticality scores for these materials are weighted by the mass of materials in the battery, the NMC battery is considered to have a higher level of criticality owing to the supply risk of cobalt. When looking at the criticality of lithium-ion batteries, it is not lithium that is of highest concern, but rather other metals in the cathode and anode, particularly cobalt.

The supply chain issues are discussed in detail below for key materials and important supply chain characteristics underpinning the criticality assessment are summarised in

Table 4. Criticality is nation specific and changes with time, and various methodologies are used for assessment. This means the assessments done by different countries or methods can vary considerably. Three measures of 'criticality' are given in this table, including:

- the European Commission measure based on economic importance and supply risk to the European Union; results are given as "critical" or "near-critical" (European Commission 2014c)
- the Yale University measure of Supply Risk based on geological, social and geopolitical factors of global criticality (this is one of three measures given in the Yale methodology, alongside vulnerability to a restriction in supply and environmental implications); results are given as a range from low to high (Graedel et al. 2015)
- the ranking given by Geoscience Australia on how critical metals are considered by other countries, this method is the least rigorous and not specific to Australia but based on an average of rankings from criticality assessments from the UK, EU, US, South Korea and Japan; results are given as a score and a category from one (high) to three (low) (Skirrow et al. 2013).

Note that while these are useful for understanding the global supply chains for key materials, none of the measures given are specific to the Australian context highlighting a need for further research in this area.

Table 4. Battery material supply chain characteristics underpinning the criticality appraisal

	Main producers	Main reserves	Energy storage as share of end-uses	Ranking of criticality	Yale ranking of criticality	Aus ranking of criticality
Key reference	U.S. Geological Survey, 2016	U.S. Geological Survey, 2016	European Commission, 2014a	European Commission, 2014c	Graedel et al., 2015 *(Supply Restriction criteria only)*	Geoscience Australia, 2013 *Category (score)*
Graphite	China 65%, India 15%	Turkey 40%, Brazil 30%, China 25%	Batteries 4% (Electrodes 30%)	Critical	Not included	Category two (8)
Lithium (Li)	Australia 40%, Chile 35%	Chile 54%, China 23%, Argentina 15% (Resources: Bolivia 22%, Chile 18%)	Batteries 22%	Near-critical	Low-medium	Category one (14)
Cobalt (Co)	Democratic Republic of Congo 50%, China, Canada, Russia, Australia ~5% each	Democratic Republic of Congo 48%, Australia 15%	Batteries 30%	Critical	Medium	Category one (21)
Fluorspar	China 60%, Mexico 18%	South Africa 15%, Mexico 13%, Mongolia 8%	Batteries <5% (Hydrofluoric acid 52%)	Critical	Not included	Category two (6)
Phosphate rock	China 45%, Morocco & Western Sahara 13%, USA 12%	Morocco & Western Sahara 72%, China 5%	Batteries <5% (unknown) (Agriculture 95%)	Critical	Not included	Not included
Nickel (Ni)	Philippines 21%, Russia 9%, Canada 9%, Australia 9%	Australia 25%, Brazil 13%	Batteries <5% (unknown) Stainless steel 61%	Not included	Low	Category one (13)
Manganese (Mn)	South Africa 35%, China 17%, Australia 16%	South Africa 32%, Ukraine 22%, Australia 15%	Batteries (cathodes) 2% (Construction 25%)	Not included	Low	Category one (12)
Lead (Pb)	China 50%, Australia 13%	Australia 40%, China 18%,	Batteries 90% (*U.S. data from U.S. Geological society)	Not included	Low-medium	Category three (3)
Antimony (Sb)	China 76%, Russia 0.5%	China 48%, Russia 18%	Lead-acid batteries (automotive) 20%	Critical	High	Category one (14)
Vanadium (V)	China 50%, South Africa 25%	China 33%, Russia 33%, South Africa 25% Australia 12%	Batteries 1% (Steel alloys 85%)	Near-critical	Low-medium	Category one (13)

GRAPHITE

Natural graphite is considered critical according to the EU commission owing to supply risk with China currently producing 65% of the world's supply and consuming 35% (U.S. Geological Survey, 2016). , China produces about 95% of the world's battery grade graphite. Although graphite can be found in many locations, including significant reserves in Turkey and Brazil, Chinese natural graphite is provided to the market at very low prices that discourage companies in other countries from operating mines (Whoriskey 2016).

Graphitic carbon is the primary material for the anodes of lithium-ion batteries. Major battery manufacturers such as ATL, Samsung SDI, LG Chem and Panasonic purchase anodes from Chinese companies. The Chinese company BTR New Energy Materials Co. claims to supply around 75% of global market demand for natural graphite materials for battery manufacture. The company manufactures graphitic anodes and sells graphite to other anode manufacturers, as do other Chinese mining companies including Haida, Aoyu Graphite and Hensen (Whoriskey 2016).

Other anode materials are being developed as potential replacements for graphitic carbon, including lithium, tin and silicon. Sodium-ion batteries use 'hard carbon' that is a synthetic carbon that may be considered less critical.

LITHIUM

While lithium is considered to have high economic importance by the EU Commission, it does not have a high level of supply risk so is considered 'near-critical' (European Commission 2014c). A high demand for lithium relative to current levels of production is anticipated (Simon et al. 2015a); however, there are significant lithium resources globally, with the majority located in Bolivia and Chile.

Lithium can be sourced from hard-rock ore (spodumene), from the evaporation of salt brines and from seawater. Lithium sourced from salt brines dominated the market in the 1990s due to lower production costs, however owing to growing demand from China the current market share for brine and spodumene is roughly equal (U.S. Geological Survey, 2016).

Chile is the major producer of lithium from salt brines, in the form of lithium carbonate (Li_2CO_3), alongside Argentina who began commercial production from a new mine in 2015. Australia is the leading producer of lithium from spodumene and produces a concentrate containing lithium oxide (Li_2O) (U.S. Geological Survey, 2016). Historically, lithium carbonate from South America has been the main material for battery manufacture, whereas lithium oxide from hard rock was mainly used in the glass and ceramics industries (Dunn et al. 2015). However, the global supply chain is interlinked, and China processes lithium carbonate for use in battery manufacture from spodumene imported from Australia, as well as domestic mining of both spodumene and brines (Prior et al. 2013).

The consumption of lithium for rechargeable batteries has increased significantly in recent years and will continue to drive demand for lithium (U.S. Geological Survey 2016). The security of lithium supply has become a top priority for global battery manufacturers, leading to the establishment of alliances and joint ventures between manufacturers and mining companies. Exploration for lithium is ongoing, and numerous new operations are under development, including brine operations in Argentina, Bolivia, Chile and the United States; as well as, hard rock operations in Australia, Canada, China and Finland. While Bolivia has the largest resources of lithium, estimated at 9 million tonnes, nationalistic mining policies that restrict foreign investment, and resistance from indigenous groups, have so far prevented production (Romero 2009).

COBALT

Cobalt is considered critical according to the EU Commission. The majority of the world's cobalt resources are in the Democratic Republic of Congo (DRC) and Zambia, with the DRC responsible for 50% of current mine production (U.S. Geological Survey, 2016). China is the world's leading producer of refined cobalt, 90% of which is from ore and partially refined cobalt imported from the DRC, where the mining industry is dominated by Chinese companies (Frankel, 2016).

Civil unrest in the DRC has created supply restrictions in the past that impacted global cobalt markets. In 1978 the DRC (then called Zaire) controlled a similar high proportion of current supply as it does now (around 50%) and a civil war led to a disruption in the supply of cobalt. This had a short but significant impact on manufacturing and became known as the "cobalt crisis" (Alonso et al. 2012).

Cobalt is often produced as a by-product alongside nickel, copper or gold, which makes it vulnerable to price changes in these markets, as typically only a small percentage of the revenues of the companies which mine cobalt come from cobalt. Lithium-ion batteries are the top end-use for cobalt by volume, representing nearly one-third of global uses (European Commission 2014c). As well as being the top producer of refined cobalt, China is the top consumer of cobalt, with 75 % of its consumption used in the battery industry (mostly for cathode manufacturing) (U.S. Geological Survey, 2016). The demand for cobalt in lithium-ion batteries has created new interest for investing in cobalt mining in Australia, including several projects solely targeting cobalt rather than as a by-product, reflecting the expected high future demand.

PHOSPHORUS

Phosphorus, derived from phosphate rock, is used in lithium iron phosphate (LFP) batteries, as well as in electrolytes used in other lithium-ion battery chemistries. It has a high supply risk, as production is concentrated in China, Morocco and the U.S. There are reserves in more than 35 countries, but six countries contain 90% of the remaining high-grade reserves, and Morocco alone (including Western Sahara territory) contains more than 70%. In 2008 the price of phosphate rock spiked 800% due to a range of factors including oil prices and increased demand for food and ethanol production. At the same time China imposed an export tariff of 135%, which contributed to the price spike and led to a sudden decease in supply (Cordell & White 2014).

Agriculture is the main use of phosphorus, accounting for 95% of end-uses (European Commission 2014a). There is no substitute for the role of phosphorus in agriculture and almost no recycling, though there are many technologies that make this possible. Although batteries only account for a tiny percentage of global phosphorus use, further price spikes could impact the global supply for the battery industry.

As China is the main producer of LFP batteries and the top producer of phosphate rock, Chinese manufacturers can source their requirements from domestic production and the criticality risk for phosphorus in China is likely lower. However, although China has high phosphorus production, it only holds a small percentage of the world's reserves, and would be vulnerable in the case of reduced domestic supply and future price fluctuations. Phosphorus criticality has implications for the flexibility of future markets for LFP batteries and potential for establishing new manufacturing centres outside of China. LFP batteries are considered a safer alternative to cobalt-based lithium-ion chemistries, but future supply risks could limit the uptake of this technology.

ANTIMONY

Antimony is a small but important material in many lead-acid batteries, which is the main end-use for the material. It has the highest supply risk of all the materials assessed according to the EU Commission methodology. It is one of the rarest occurring elements, and commonly mined as a by-product of gold, silver, lead or zinc (European Commission 2014b). China is responsible for three-quarters of current supply and has half of world reserves. Production declined in 2015 due to a government decision to control the resource, through the closure of smelters and consolidation of production. It was reported that 50% of production capacity in Hunan province, where the majority of mining takes place, was sitting idle in late 2015 (U.S. Geological Survey 2016).

Although it has high criticality, it can also be substituted for combinations of calcium, copper, selenium, sulfur and tin in lead-acid batteries, and the amount used in batteries has been declining over time due to these substitutes. It can also be recycled, and antimony from lead-acid batteries is recovered at lead smelters and reused in the lead-acid battery industry (U.S. Geological Survey 2016).

VANADIUM

Vanadium is a key material in the Vanadium Redox Flow (VRB) battery. VRB batteries currently have only a small market share and consequently battery manufacturing makes up only 1% of the end-use of Vanadium production, of which 85% goes to steel alloys. China is the main producer followed by South Africa, however export prices have declined in South Africa making it difficult for producers to remain profitable. A disruption in supply from South Africa could impact production of vanadium products in Austria, South Africa and the U.S., which depend on South African imports. The U.S. Geological Society (2015) expects that if prices don't increase about 2015 levels that more producers are likely to suspend production.

MITIGATION STRATEGIES

In considering less mature battery technologies there may be additional materials required that are considered critical, for example lanthanum used in solid-state batteries, which will require further investigation if these batteries emerge as prominent (Troy et al. 2016).

Disruption in the supply of materials for batteries could affect the production of energy storage batteries, and as Australia has limited battery manufacturing established onshore, this could limit the supply of batteries.

The criticality of materials can also be considered, under the assumption that Australia might establish battery manufacturing onshore. National criticality assessments have been undertaken by most major economies and the results of these assessments vary significantly at the country level owing to the existence of domestic resources and established production chains to meet demand. We are not aware of a detailed study undertaken for Australia and so it is difficult to measure the criticality of key materials for which we have resources (Ciacci et al. 2016b). For example, Australia has abundant lithium and cobalt resources, however the current limited processing capabilities and production chains could increase the criticality risk until these capabilities are established.

The Geoscience Australia report, “Critical commodities for a high-tech world” assesses the resource potential for critical commodities in Australia, based on the commodities that are considered critical in assessments undertaken by major world economies, including studies from the UK, EU, US, South Korea and Japan (Skirrow et al. 2013). This study could be expanded to look at the level of criticality of resources to Australia. Although there is often a perception that criticality is not of high importance to Australia due to our limited manufacturing industry, understanding criticality provides important insights, enabling new opportunities for industry and research, including the recovery of materials at end-of-life.

3.2.4 Material intensity

Battery production requires the use of more non-renewable metals and minerals than other storage technologies, e.g. compared to pumped hydro, batteries inherently have a higher material intensity. The material intensity of battery technologies is primarily determined by their energy density, a measure of the energy stored (Wh) per kilogram of battery, and the use of recycled content in their manufacture offsetting demand for primary raw materials. Key material intensity data for the different Li-ion battery chemistries is given in Table 5.

Lithium-ion batteries have a high energy density that means they have a lower material intensity than alternative battery technologies, although there are significant differences between the various lithium-ion chemistries. Of the major lithium-ion chemistries, LFP batteries provide less energy per unit of weight and are typically larger and heavier than NMC batteries. In other words LFP batteries have a high demand for metals per Wh of energy storage, however this demand is primarily for iron which is not considered critical (Simon et al. 2015b). Although nickel cobalt aluminium oxide batteries (NCA) have a smaller demand for metals per Wh of energy storage (although higher than NMC), because they contain a relatively large amount of cobalt, the market share of this chemistry has decreased.

Lead-acid batteries are typically manufactured with 60–80% recycled lead and plastic, and are the only battery technology to have a high level of recycled content (Sullivan & Gaines 2012). This offsets their low energy density**.**

Flow batteries have the lowest energy density out of the batteries considered, and therefore their material intensity is higher than the alternatives. However most of the materials used are not considered critical.

Sodium-based batteries have a high energy density, and therefore low material intensity. The materials used are also not considered critical.

Table 5: Material demand for major lithium-ion battery chemistries, based on data from Simon et al. (2015)

Battery chemistry	Cobalt (kg/kgWh)	Nickel (kg/kgWh)	Lithium (kg/kgWh)	Manganese (kg/kgWh)	Iron (kg/kgWh)	Aluminium (kg/kgWh)
NMC	0.021	0.41	0.13	0.41		
LFP			0.16		1.23	
NCA	0.29	1.57	0.24			0.04

3.2.5 Recyclability

As discussed above, recycling can have an important impact on the lifecycle energy demand, GHG emissions and material intensity by offsetting demand for primary materials. The current status of recycling, with a focus on the Australia context, is given below.

USED LEAD-ACID BATTERY (ULAB)

ULAB recycling of car batteries is well established, with the value for lead offering a profitable return for recyclers. It is estimated that 80–90% of all lead-acid batteries are recycled in Australia, depending on the application (i.e. about 90% for automotive and 80% for other uses). Upon collection the estimated diversion of materials from landfill is > 97% demonstrating the efficiency of the recycling process. Current capacity in Australia to recycle lead is about 200 000 tonne p.a., and we are aware of some companies importing ULAB for recycling in Australia. The lead that is recycled in Australia is sold predominantly to battery manufacturers (~ 90%) mostly located in Thailand, Korea, Taiwan and Malaysia. Recycled lead can displace virgin lead up to 60-70% in the manufacture of new lead-acid batteries.

ULABs are a 'controlled waste' and this means that a waste storage and transport license is required in most states and territories, with tracking required for interstate transport. Because the transport of end-of-life batteries is categorised as dangerous good transport, it must be carried out according to the Australian Dangerous Goods codes that are well established for this technology. Classification as a hazardous waste means that the export of ULABs is only allowed under permit. Presently, there is a bill for an Act to Amend the Hazardous Waste Act 1989 (Australian Government 2016) that if passed will potentially create an incentive for greater local investment to maintain and expand local recycling infrastructure by increasing the cost of export (Australian Battery Recycling Initiative 2015).

OTHER RECHARGEABLE BATTERIES (LI-ION, SODIUM-BASED CHEMISTRIES, FLOW BATTERIES)

The discussion in this section focuses mainly on lithium-ion batteries owing to their anticipated market dominance in the timeframe considered in this review. Most lithium-ion batteries are technically recyclable but technologies are still under development and the recycling efficiency is dependent on the pathway used. The main driver is metals recovery (cobalt, nickel, copper). In Australia, at present, there is neither the economic driver nor a policy incentive for recycling and most recyclers charge a gate fee. It is estimated that about 3–5% of rechargeable batteries (all non-ULAB technologies and applications) sold onto the Australia market are collected (Australian Battery Recycling Initiative 2015).

Owing to the very small volumes of Li-ion batteries collected, there is very limited incentive for recyclers to invest in on-shore processing. Broadly speaking, the recycling of materials from these batteries is a two-stage process: The pre-processing involves shredding, sorting and separating out the metals. After these 'breaking' and separation processes, metals, plastics, paste and a metal containing dust are directed towards different resource recovery pathways. The dust (representing 30–40% by mass of the battery) is where the value is, as it contains cobalt and nickel. The second step involves hydrometallurgical processing to recover the cobalt and nickel for manufacturing.

The Li-ion batteries that are collected in Australia are typically only sorted by chemistry and exported overseas for recycling, which is mostly happening in South Korea, Japan and Europe. We are aware of one exception – PF Metals – that is capable of doing the 'breaking' on-shore to produce the dust; the company has recently applied for an export permit to send the dust to recyclers overseas.

Other technologies (sodium-based chemistries, flow batteries) are technically recyclable but pathways remain under development given that these are new technologies (Australian Battery Recycling Initiative 2015).

Establishing viable recycling pathways is very challenging owing to uncertainty with respect to technology development. The wide range of battery chemistries under development and the paucity of data regarding when, where and what batteries will reach their end-of-life stage creates significant doubt for battery recyclers in terms of evaluating the potential value of recycled materials and components. Lithium-ion battery chemistries under development have less or no cobalt, and thus their value for recycling is limited to other components including copper, high-purity electrolytes (for reuse in new cells), processed carbons, and aluminium and steel casings.

Rechargeable batteries are also classified as a hazardous waste under the *Hazardous Waste (Regulation of Exports and Imports) Act 1989.* However, apart from the Act there is currently no Australian legislation or regulation requiring manufacturers and retailers to participate in responsible disposal of battery storage technologies.

BOX 1: Product Stewardship in Australia (Florin et al. 2016)

The Australian *Product Stewardship Act 2011* is a legislative framework that guides the lifecycle management of products in Australia with the aim of minimising health and environmental impacts. The Act is designed to distribute responsibility among producers, sellers, users and disposers. Each year a list is published of products being considered for inclusion under the Act. Photovoltaic systems and large storage batteries were listed separately by the federal government for consideration under the *Product Stewardship Act 2011* in 2016–17. Listing provides a signal to the market of the government's interest in evaluating the rationale and feasibility of some form of stewardship for PV systems and/or energy storage batteries under the Act for the next financial year.

Under the Act there are three categories of stewardship: 1. Voluntary stewardship comprises industry schemes that are accredited and operate without regulation. Organisations with accreditation are obligated to operate transparently and accountably. Currently there are two accredited voluntary schemes – Mobile Muster (mobile phones) and Flurocycle (mercury containing lamps). 2. Co-regulatory schemes, like voluntary schemes, are run by industry, however they are regulated by government in terms of specific operational requirements, like waste management targets. Regulations are formed separately around each scheme. The National Television and Computer Recycling Scheme (NTCRS) is the only example of a co-regulatory approach. 3. Mandatory product stewardship legally obliges specific parties to undertake specific actions around the management of products. Under the act, the Australian Government is designated as the Regulator and assigned specific powers. Compliance is legally enforceable and parties can be penalised for breaches. Currently, there are no mandatory schemes.

As well as the current listing of PV systems and large storage batteries, all batteries were also recently listed under the Product Stewardship Act and industry is currently evaluating the challenges and opportunities associated with creating a nationwide battery stewardship scheme in Australia. This effort is important in the broader energy storage environment both in terms of early learning and the potential for leveraging efforts to ensure that emerging energy storage stewardship initiatives are designed in an efficient and cost-effective manner.

Towards pursuing a product stewardship approach to energy storage in the PV sector in Australia, in November 2016 the Meeting of Environment Ministers (MEM) endorsed the establishment of a Victoria-led jurisdictional working group to work with the PV sector to develop a national product stewardship approach for PV systems, subject to funding requirements and assessment of timeframes.

Insights from existing product stewardship approaches

There is an opportunity to gain insight from approaches to product stewardship in Australia. There is an opportunity to build on the successful elements of the NTCR scheme, noting the opportunity to leverage the experience in the product stewardship community of improving the NTCR scheme through two iterations.

Relevant insights from this experience are:

- Understanding realistic timeframes needed to develop and implement a successful scheme at least about 10 years;
- Recognising the challenge and importance of getting all stakeholders on board (active and early engagement with all industry stakeholders is essential);
- Identifying critical intervention points in the supply chain (e.g. retail and installation);
- Leveraging synergies with other policy levers (e.g., landfill levies); and
- Developing detailed analyses of the material and value flows at the national level

As well as the bill to amend the Hazardous Waste Act (discussed above), another important developments relevant to stationary energy storage batteries is the listing of PV systems and batteries (energy storage and handheld) for consideration under the *Product Stewardship Act 2011.* A brief overview of product stewardship approaches in Australia is provided in Box 1 below.

Whilst this discussion has focused on recycling, there are other niche resource recovery pathways including reuse. One promising example that is championed by Relectrify involves 'rebirthing' batteries from electric vehicles at the end of their first life for storage applications.

3.2.6 Environmental health

The impact of batteries on environmental health varies depending on the location of mining, material processing and disposal or recycling at end-of-life. This is due to differences in technology, production routes and local environmental and social standards. A summary of impacts is given in Table 6.

For lithium-ion batteries, the materials in the cathode have the most adverse impacts on the environment and those containing nickel and cobalt – specifically NCA, NMC and NCO – have the most significant impact burdens (Schmidt et al. 2016).

Table 6: Environmental health impacts from mining of battery materials

	Main producers	**Environmental health impacts**
Graphite	China 65%, India 15%	China: Air pollution from graphite dust, leading to respiratory ailments, Water pollution from acids into local water sources including drinking water
Lithium	Australia 40%, Chile 35%	Australia: large volumes of waste rock, high water use Argentina & Chile: Water pollution and depletion; leaching, spills or air emissions of chemicals
Cobalt	Democratic Republic of Congo 50%, China, Canada, Russia, Australia ~5% each	DRC: Air, soil and water pollution leading to heavy metal contamination of communities, health impacts including thyroid conditions, respiratory ailments and birth defects
Phosphate rock	China 45%, Morocco & Western Sahara 13%, USA 12%	China: large volumes of waste rock, contamination of water with uranium, arsenic and cadmium with human health impacts; Namibia: Potential risk for seabed mining
Lead	China 50%, Australia 13%	China: Heavy metal contamination of water, soil and plants with lead and cadmium; Serious human health impacts especially for children.

GRAPHITE

China is the primary producer of graphite for use in batteries, and dust from mines and plants in China pollutes air and water, and damages human health of local residents. Graphite mining occurs mainly in remote Heilongjiang Province in the northeast of the country on the Russian border, but also in the more populous Shandong Province south of Beijing (Whoriskey 2016).

Air pollution from graphite occurs when there are inadequate systems to keep the fine graphite powder/dust from becoming airborne. The fine dust can cause respiratory ailments including breathing difficulties and aggravate lung disease, and has been linked to heart attacks.

The chemicals used in the purification process, such as highly toxic hydrofluoric acid, cause water pollution if they leak or are discharged into local water sources. Residents living near mines have reported the chemical discharge has an odour and irritates the respiratory system, pollutes drinking water and damages crops. There are less hazardous methods of purification that do not use acids, but these are not used often in China owing to the higher cost (Whoriskey 2016).

Graphitic carbon can also be produced synthetically, however this process is extremely energy intensive and is typically derived from petroleum coke, and is currently not cost effective compared to natural graphite. There are also issues with the purity of synthetic graphite that make it less desired for battery production.

LITHIUM

Lithium production is widely considered to have lower adverse environmental impacts than other battery materials, such as cobalt and nickel. In terms of overall environmental impact (including energy demand and GWP), the production of lithium carbonate from brines or ore does not differ substantially. Recovery of lithium from seawater, which is not currently commercially viable and unlikely to be in the near future owing to the very low concentrations, is likely to have a much higher impact associated with the energy intensity (Stamp et al. 2012).

The mining of lithium from hard rock spodumene, which occurs mainly in Australia and China, is energy intensive and uses large volumes of water. Large quantities of waste rock and tailings are produced because large volumes of spodumene need to be processed to obtain the lithium that exists in low concentrations (Prior et al. 2013).

The biggest lithium brine resources are located in the 'lithium triangle' between Argentina, Bolivia and Chile, in arid areas where access to water is important for local communities and biodiversity (Friends of the Earth 2012). To produce lithium from brines, holes are drilled into the salt flats (*salars*) to pump brine to the surface where it is concentrated into lithium carbonate in evaporation ponds. The evaporation process uses large volumes of water and the long-term environmental impacts on local water systems are uncertain. Lithium mining could have severe consequences for biodiversity and human health in the region because of decreased freshwater availability and water contamination (Wanger 2011). Chemicals used in the processing can harm the environment if released through leaching, spills or emissions into the air (Friends of the Earth, 2012).

In the Salar de Atacama in Chile where lithium has been mined since the 1980s, the salt lakes have been declining in size, although the cause is unknown. Mining companies operating in the area, including Chilean-owned SQM and US-owned Albemarle, have been accused of violating rules on the use of water for lithium extraction and creating environmental problems. In Argentina, the two major operations are Sales de Jujuy, a joint venture between Australian Orocobre, Japanese Toyota Tsusho and the provincial government JEMSE, and Minera Exar, a joint venture of SQM and Canadian company Lithium Americas. Both companies were fined by the government in 2016 for environmental offences in the Cauchari and Olaroz salars (Frankel & Whoriskey 2016). Local communities in the Salar de Hombre Muerto in Argentina claim that lithium mining has contaminated local water sources relied on for agriculture and livestock (Friends of the Earth, 2012). Bolivia has the largest lithium resources but has yet to begin industrial scale mining of lithium. There is local resistance to planned development of mining in the Salar de Uyuni due to the high water use and environmental impacts of silver mining in the area.

COBALT

As discussed above, the majority of the world's cobalt is mined in the DRC, where mining impacts the local environment and the health of miners and residents in the surrounding communities. The border between Zambia and the Democratic Republic of Congo, known as the African Copperbelt, is considered one of the top ten most polluted areas in the world (Narendrula et al. 2012). Cobalt ores are mined in industrial and hand-dug artisanal mines, and both types of mines, as well as local smelters, contribute to environmental pollution.

Cobalt is primarily produced as a co-product of nickel or copper mining. In the DRC it occurs alongside copper mining, and cobalt mined in the DRC is the primary source of cobalt for lithium-ion batteries, due to the suitability of copper-cobalt oxides for battery manufacturing (Schmidt et al. 2016). There are a large number of mining companies operating in the DRC, including the state-owned company Gécamines, and Canadian, Australian, European and Chinese companies, sometimes in joint ventures with Gécamines. It is estimated that there are around sixty Chinese companies operating in DRC, including smelters and depots where cobalt is traded before processing or export (Goethals et al. 2009).

Mining of cobalt in the DRC is typically done using open cut or underground methods with crushing, grinding and flotation, followed by smelting and refining. There is little information of the impacts of mining on the local environment but mining operations have taken little control over the discharge of pollutants from mines or smelters, leading to contamination of air, water, soil and plants with heavy metals (Dunn et al. 2015). A survey of workers in several Chinese-owned companies reported that the companies did not respect environmental standards and created pollution (Goethals et al. 2009). Artisanal miners contribute to pollution as the cobalt ores are washed in local water sources used for cooking and drinking (Tsurukawa et al. 2011).

The health impacts of cobalt mining in the DRC are significant. Artisanal miners are particularly exposed to heavy metals through environmental pollution, dust inhalation and exposure to high concentrations of uranium in the mines (Tsurukawa et al. 2011). A study of the Katanga area where mining is prevalent found high exposure of the surrounding populations to several metals, including cadmium, cobalt, arsenic, lead and uranium and exposure levels were especially high in children. The concentrations of cobalt in this area are the highest ever reported in human populations (Banza et al. 2009). In areas where mining and smelting takes place the general population is exposed from their environment, even if they do not work in cobalt mining or refining. A further study in the area found concentrations of cobalt in the population are correlated with levels in the drinking water, vegetables and fruit. The main source of exposure is through the diet and cobalt transfer from soil and water in the food chain, and dust ingestion also contributes substantially to the exposure levels of children (Cheyns et al. 2014).

Studies are currently underway to understand the health impacts of the high exposure to heavy metals in the area, including thyroid conditions and breathing problems; there is also a potential link to birth defects. Rare birth defects have been reported in regions with heavy mining, including one syndrome unique to the DRC (Frankel 2016).

OTHER KEY MATERIALS

Phosphate rock mining has a high impact on the local environment. Surface mining of phosphate rock deposits involves removing vegetation and the top layers of soil and rock to expose the resources, which impacts local ecosystems, air and water quality (Schröder et al. 2010). The impacts have been studied in China and shown to be severe, including loss of forest quality, loss of biodiversity, desertification and increased likelihood of landslides and erosion. The mining process creates large volumes of waste rock, for example in one Chinese mine the area of land for waste rock was five times as large as the mining area. To mitigate this impact, the waste rock can be used to rehabilitate the mining site, which has been done successfully along with revegetation (Yang et al. 2014). Phosphate rock mining can cause sever water pollution, and has been linked to contamination with uranium, arsenic and cadmium of water sources China, which can cause ecosystem and human health impacts (Wang et al. 2014).

Demand for phosphorus has also led to the controversial proposal of two mines off the cost of Namibia to mine phosphate rock from the sea bed, which would severely impact the local marine ecosystem (Cordell & White 2014).

Heavy metal contamination is a serious impact of lead mining in China. Heavy metals released from mining and smelting, including lead and cadmium, can contaminate soil, water and plants, including crops. The human health impacts of lead are well understood, including damaging key body systems and effecting development in children, and lead-related health problems remain a serious issue in China (Zhang et al. 2012).

MITIGATION STRATEGIES

Environmental management strategies can reduce the impact of mining on the environment, driven by voluntary standards, corporate responsibility or government legislation. Any strategy to reduce the local impacts on environmental health needs to make sure the problems are not just shifted elsewhere.

Standards can cover the mining process and the value chain through chain-of-custody. There are multiple mining standards in use. An example is the Standard for Responsible Mining under development by the Initiative for Responsible Mining Assurance (IRMA) to certify the environmental and social performances of mine sites. Environmental responsibility is one of four areas considered, alongside business integrity, social responsibility and positive legacies (IRMA n.d.). It is widely considered that the best international standards are those in line with the principles and codes of practice of the ISEAL alliance, an organisation that aims to improve the impact and effectiveness of sustainability standards. This includes the principle that they are transparent and developed in a multi-stakeholder process (ISEAL Alliance n.d.).

Chain-of-custody standards are to ensure that resources are tracked through the value chain from production to final product, and are applied to processors or manufacturers. Existing chain-of-custody standards include the Responsible Jewellery Council, Responsible Steel and the Aluminium Stewardship Initiative. There is currently no chain-of-custody standard for other metals including lithium, graphite and cobalt.

For corporations, ethical sourcing practices and Corporate Social Responsibility commitments can ensure better environmental management. Corporations should make sure they respect international laws, adopt best practice standards, and undertake sustainability reporting. National legislation can also be a lever to promote environmental standards. For example the EU has recently introduced a directive that requires large companies to report on environmental and social aspects of their supply chains (European Commission 2016).

It is important that these environmental impacts are managed. These impacts risk undermining the potential benefits with the transition to low-carbon renewable energy system and shifting environmental burdens elsewhere. Australian mining companies and governments need to be aware of international initiatives and are in an ideal position to take a leadership role.

3.3 Social Impacts

3.3.1 Human rights

Human rights impacts are associated with the material demand for lithium-ion batteries. Here, we focus on the mining of lithium and cobalt as the two major issues.

LITHIUM

Mining in the 'lithium triangle' has led to water-related conflicts and concerns over lack of adequate compensation for the local communities (Dunn et al., 2015). There is little published research on the impacts of lithium mining in this region, but reporters and NGOs have been investigating the issue. In Chile and Argentina, lithium mining occurs on the land of the indigenous Atacama people. The mining has created division in indigenous communities, with some community members opposed to mining in the salt flats that are considered sacred. Others are grateful for the new job opportunities in the mines that pay relatively high wages in a region where there are few job opportunities.

In Chile, the Atacama people remain in poverty, despite decades of lithium mining. Lithium mining began in the Salar de Atacama in the 1980s with US company Foote Mineral and the deal with Chile and the indigenous people has been described as "unfair". Albemarle who currently owns this operation was not required to make payments to the indigenous groups until a new agreement was established in 2016; the company is now expected to make payments to the communities equivalent to 3% of annual sales (Frankel & Whoriskey 2016).

Operations under development in the Argentina include annual payments to local communities for their water rights, however communities feel that this is inadequate compensation. Minera Exar in the Cauchari-Olaroz Salars have made a deal with six local communities for an annual payment of between $9000 to $60000 per year, but are expected to make $250 million a year in sales (Frankel & Whoriskey 2016).

Of largest concern to communities is that lithium mining could contaminate water sources and divert water away from local communities, worsening existing water shortages (Friends of the Earth, 2012). The area has experienced drought for several years and water is critical for communities, including for agriculture and grazing.

COBALT

The mining of cobalt in the DRC has significant adverse human rights impacts, namely the dangerous conditions of artisanal mining, poor working conditions in industrial mining companies, and extensive child labour.

Over the last decade, 60–90% of cobalt exported from the DRC has come from artisanal and small-scale mining (ASM), which is done in dangerous conditions where deaths and injuries are common (Tsurukawa et al. 2011). There are an estimated 100 000 artisanal cobalt miners who mine by hand-digging tunnels deep underground without proper tools, safety measures or protective equipment (Frankel, 2016). The miners face a constant risk of cave-ins or landslides, particularly during the rainy season (Tsurukawa et al., 2011), and death by suffocation or drowning (Goethals et al., 2009).

In the early 2000s mineral resources in the DRC were privatised to drive investment and concessions were granted to foreign mining companies. Artisanal miners were excluded from large areas of land they had mined for the previous decade, and a small number of Artisanal Mining Zones (ZEAs) were established in areas unsuitable for industrial mining. As the areas zoned for artisanal mining are limited, artisanal miners often illegally mine in concessions owned by large companies during the night where the safety risks are increased (Goethals et al., 2009). Miners also dig for cobalt from tailings of active or inactive concessions. There are reports that officials extort illegal payments from artisanal miners for mining in illegal areas (Amnesty International 2016).

Child labour is widespread and it is estimated that there are between 19 000 and 30 000 children under 15 years of age working in artisanal cobalt mines (Tsurukawa et al., 2011). Children collect minerals from tailings of industrial mining concessions or sort and wash ores, and some are also sent digging in narrow mines. This work is particularly dangerous to children, as they often carry heavy bags of ore and this can result in long-term injuries. In addition they are at risk of physical abuse and financial exploitation (Amnesty International 2016).

Artisanal miners sell their cobalt to local trading houses, many of them Chinese, and without knowledge of global commodity prices they are not able to negotiate a fair price. Despite this, artisanal workers earn higher wages than average, and artisanal cobalt mining provides income to a significant share of the population in the region (Tsurukawa et al. 2011).

The majority of artisanal cobalt ends up with Chinese company Congo Dongfang International Mining (CDM), one of the country's largest mining companies and the biggest exporter of artisanal cobalt. The ore is smelted in the DRC before it is shipped to CDM's parent company Zhejiang Huayou Cobalt in China, one of the largest cobalt producers worldwide, where it is further refined. Huayou is one of biggest suppliers of cobalt to battery cathode manufacturers in China and South Korea, and these cathodes are then sold to major battery manufacturers worldwide (Frankel 2016).

Belgium-based Umicore is another of the world's largest cobalt refiners and a major supplier of materials for lithium-ion batteries. They buy cobalt from the DRC, but have a procurement policy to only buy from industrial mines and conduct their own assessment of suppliers (Umicore n.d.). However, it is difficult for downstream companies to know if their supply contains cobalt from artisanal mines, as the supply chain is so complex and ores may be mislabelled as legally mined (Tsurukawa et al. 2011).

The majority of foreign mining companies in the DRC are Chinese owned. There are of estimated to be around 60 Chinese-owned companies, including smelters and trading houses. Workers in Chinese companies report that they are not provided adequate protective clothing and there is a lack of training and safety procedures. It is reported that workers are not provided with facemasks and are exposed to harmful dust and radioactive minerals. In the case of accidents workers do not receive adequate medical attention or compensation for serious injury. They work long hours and have reported that assaults and beatings by security guards are common. Children as young as ten have been reported working in the Chinese trading houses, and the minerals traded and processed by Chinese companies are often from artisanal mines that may include child labour (Goethals et al., 2009).

Most workers have a lack of job security as they are hired on a casual basis, so that the company is not required to pay for their insurance. Those that do have contracts still have little protection as their contracts are written in Chinese and they risk being arbitrarily dismissed for trivial or false offences. Workers do not receive the same benefits, such as medical care, set working hours and overtime, as those employed by the state-owned Gécamines (Goethals et al. 2009). They are often employed on a casual basis for longer than the period of 23 days, after which they have a legal right to a permanent contract (Tsurukawa et al. 2011).

Both the Chinese and the DRC governments have ratified international human rights standards that should be respected by mining companies. These include the International Covenant on Economic, Social and Cultural Rights, the Convention on the Rights of the Child and International Labour Organisation (ILO) standards on elimination of discrimination in respect of employment and occupation and on the elimination of child labour (Goethals et al. 2009).

MITIGATION STRATEGIES

To end human rights impacts in industrial mines, international mining companies have a responsibility to follow international human rights standards, including standards on child labour. Where the lands of indigenous people are involved, mining companies have a responsibility to obtain the free, prior and informed consent of communities, as recognised in the UN Declaration on the Rights of Indigenous Peoples. This entitles indigenous people to make decisions about projects that may affect their environment and livelihoods, in a process that is free of coercion, provides all relevant information, and is done before a project commences (International Council on Mining and Metals 2013; UN OHCHR 2013). Local communities whose access to land or resources is affected by a project should be properly compensated and there should be efforts to provide employment opportunities for local communities.

There is a lack of agreement on how to mitigate the impacts of artisanal mining. One strategy is to avoid sourcing of minerals from artisanal mines, as Umicore has done with their Sustainable Procurement Framework. Various initiatives have been implemented to prevent mining that supports ongoing conflict in the DRC, which is often linked to artisanal mining. However cobalt is not currently included in these initiatives.

Current initiatives focusing on this problem include the voluntary 'OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas'. This document provides guidance on sourcing from artisanal mines and the Umicore framework is based on it. Section 1502 of the US Dodd-Frank Wall Street Reform and Consumer Protection Act is a regulatory approach which requires US companies to disclose whether they are receiving tantalum, tungsten, tin or gold from the DRC, and whether they are connected to conflict. There is also a 'Conflict-free Smelter Program' developed by the Conflict-free Sourcing Initiative that certifies smelters and refiners that produce conflict-free materials (tantalum, tungsten, tin and gold) from the DRC, in line with the Dodd-Frank Act.

The Dodd-Frank act has been criticised for misunderstanding the relationship between minerals and conflict. It is claimed that a decreased consumption of metals from the DRC in global markets has led to increased poverty as miners are left with few options (Raghavan 2014). The OECD approach however aims to ensure that the standard allows artisanal mining communities to continue to benefit from mining (OECD 2016).

On the other hand there are proponents of artisanal mining who believe the industry should be transformed and supported, to reduce the environmental and social impacts and create an industry that contributes to sustainable development (World Bank 2013).

One approach to support ASM is through the formalisation of the sector and development of sustainable supply chains through certification standards, as is promoted by the OECD. However there are mixed opinions on whether the formalisation of ASM is the best pathway forward, due to the vast scale of artisanal mining and the increased costs for miners to join a certification scheme. Any formalisation process needs to be inclusive, to make sure that it does not increase inequality by being only achievable for the miners who have existing advantages such as more access to land (Blackmore et al. 2013).

Current standards for artisanal mining include Fairtrade International and the Fairmined Standard for Gold and Associated Precious Metals, developed by the Alliance for Responsible Mining. The uptake of these standards has been limited but is increasing; to date the Fairmined standard has been applied to gold mining in six artisanal mining organisations in four countries (Alliance for Responsible Mining n.d.). Companies that source from artisanal mines could support the implementation and expansion of these standards to cobalt. The IRMA standard, while developed for large-scale mining, is collaborating with initiatives for responsible small-scale and artisanal mining to ensure that the standard does not result in unintended consequences for ASM (IRMA n.d.).

To improve human rights impacts relating to cobalt mining in the DRC, it is not recommended that there be a blanket ban on cobalt sourced from artisanal sources. Instead, actions to support artisanal miners could include the expansion of artisanal mining zones to provide more legal mining areas, and ensuring fair payment to miners through a central point (Tsurukawa et al. 2011). Downstream industries and donors could support the local government agency that supports ASM, support formalisation processes, and cooperate with artisanal miners to mitigate human rights, environmental and health hazards.

Apple announced in early 2017 that it is working with Huayou (the largest Chinese supplier of artisanal cobalt) on a program to improve the safety of working conditions and remove child labour from artisanal mines. The company position is that they will not ban sourcing from artisanal mines as it provides income to local people, but have put a temporary halt on purchasing cobalt from artisanal mines until they are verified according to their own internal standards (Frankel 2017).

International mining companies can also support artisanal miners, where appropriate alongside local governments, to demonstrate accountability in the local context. The World Bank project Communities and Small-scale Mining (CASM) provides a list of ways in which large-scale miners can contribute to Corporate Social Responsibility efforts with artisanal miners. This is of particular complexity where large-scale miners have mining rights that were previously held by artisanal miners (CASM, 2009), as is the case with cobalt mining in the DRC (Goethals et al. 2009). Actions can include promoting better legal and regulatory mining frameworks, assisting with organisation and formalisation, providing finance for technical assistance and providing training in mine management and safety, and creating employment opportunities (CASM, 2009). One of the main drivers of child labour is high school fees, so corporate responsibility initiatives to eliminate child labour could make this a priority (Amnesty International 2016).

3.3.2 Health and safety

Energy storage batteries are classified as ‘dangerous goods’ and appropriate risk management strategies, including safe handling and storage advice, significantly mitigate the potential risks. The range of risks are categorised according to different lifecycle phases: handling, transport, storage and end-of-life (Table 7).

LI-BATTERY FIRES

In the context of the anticipated dominance of Li-ion, the potential for thermal runaway leading to fire and explosion is considered a very significant safety issue with broad potential impact along stages of the supply chain including: transport, handling, storage, installation, decommissioning and end-of-life. Li-battery fires (not specifically stationary energy storage batteries) have been widely reported in the context of transport, storage and in landfills. The risk has received most public attention in the context of the recall of Samsung Galaxy Note 7 smartphones (Weise 2016). The fire risk is well known and mitigated by design modification, appropriate installation, monitoring and management systems, as well as adherence to safety protocols at end-of-life.

In the different Li-ion battery chemistries (e.g., NMC, LFP) most of the metal-oxide electrodes are chemically unstable and can decompose at elevated temperatures potentially leading to thermal runaway and the risk of fire. LFP have been designed to reduce the risk of thermal runaway compared with other Li-ion chemistries, and are thus widely regarded as safer. In the case of Li-ion batteries, to minimise the risk of thermal runaway, the technology is incorporated with a battery management system (BMS). The BMS monitors the voltage level of each cell in the battery bank when charging and discharging. Overcharged cells and cells discharged to below the minimum voltage point can cause cell failure. Given the wide range of chemistries, it is important that the BMS is tailored to the individual battery type and this highlights the importance of system designers and installers having good awareness of the wide variety of chemistries requiring specific BMS (Cavanagh, Behrens, et al. 2015). Alternative technologies, e.g., sodium-based chemistries use non-combustible materials that eliminate fire risk.

Table 7. Health and safety risks for energy storage batteries after (Cavanagh, Behrens, et al. 2015; U.S. Department of Energy 2014; Cockburn 2016; CEC 2016; Australian Battery Recycling Initiative 2008; Australian Battery Recycling Initiative 2015)

Health and safety risk	Mitigation strategy
General safety risk	
Fire or explosion	Further data needed characterising conditions affecting fire risk different chemistries (major Li-ion chemistries are very unstable with potential for thermal runaway [overheating]) Use alternative battery technologies (sodium-based chemistries use non-combustible materials eliminating risk, LFP have lowest safety risk of Li-ion) Avoid exposure to sparks or flames Adhere to safe installation guidelines and standards regarding locating batteries Initiate appropriate emergency response in case of fire
Electric shock hazard	Avoid contact with terminals Avoid contact with conductive materials Insulate terminals
Handling	
Stored energy hazard	Appropriate protection from short circuits, faults or accidents owing to incorrect use is required as batteries contain enough energy to be a hazard
Chemical hazard	Material Safety Data Sheets (MSDS) are required to determine specific risk mitigation strategies for different chemistries Wear personal protective clothing (batteries contain chemical energy and electrolyte material e.g. sulphuric acid used as electrolyte in lead acid can cause burns and may be a hazard in the event of leakage owing to a damaged casing) Initiate appropriate action in case of spill
Flammable/toxic emission hazard	Avoid exposure to sparks or flames, e.g. lead-acid batteries emit a corrosive and potentially explosive mix of H_2 and O_2 during last stages of charging mitigated by adequate venting; rupture of the Li-ion battery, can result in emission of gases that may contain carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2) and traces of hydrogen fluoride (HF) Further data is needed on which chemistries may produce toxic gas and under what conditions
Cascading battery cell failure	Initiate appropriate shut-down
Temperature fluctuations	Avoid exposing battery to extreme temperatures Closely monitor performance under extreme temperatures
Arc, flash or burn	Avoid contact with conductive material likely to lead to short circuit, as short circuiting can lead to high temperatures (no specific details or standards to address this risk)
Manual handling	Adhere to proper manual handling procedures
Gravitational hazard	Install batteries appropriately to avoid potential of battery falling in event of external force
Land, sea, air transportation	Follow transport codes (owing to classification as dangerous goods there are specific codes and procedures for on land, sea and air

	transport, e.g. for transport by land different chemistries may not be loaded on the same pallet) Further standards development is needed for all technologies (most developed for lead-acid) Avoid micro-movements and don't store Li-ion batteries for more than 6 months (for Li-ion micro-movements can increase risk of short circuit)
Storage	
Containment	Store in cool, dry, well ventilated area (exposure to high temperature is known to reduce lifetime of certain Li-ion chemistries)
Battery short circuit	Avoid exposure to water and/or variable temperatures that may lead to short circuit Undertake maintenance regularly
End-of-life	
Hazardous waste	Properly identify chemistry type (check label or contact manufacturer) and avoid mixing different technology classes Keep away from potential ignition sources Assess for damage and/or leaks and take appropriate action if spill occurs For organisations that store or handle end-of-life batteries, adhere to environmental and work place health and safety obligations (including appropriate training for staff) For personnel handling end-of-life batteries, wear protective clothing
Residual charge	Always assume batteries carry charge End-of-life batteries should be decommissioned and removed by trained personnel Avoid potential for electric shock by avoiding contact with conducting material and insulate terminals Avoid vibrations in transport (for Li-ion, micro-movements can increase risk of short circuit).

STATUS OF THE MITIGATION AND MANAGEMENT STRATEGIES

Owing to the relative immaturity of the industry, significant focus has been directed toward ensuring safe installation. A comprehensive CSIRO review published in November 2015 commissioned by the Clean Energy Council (CEC) titled 'Energy storage safety: Responsible installation, use and disposal of small-scale commercial systems' identified a number of important safety issues and priority initiatives (Cavanagh, Behrens, et al. 2015). The scope of this review was 'domestic and small commercial energy storage systems (>1 kWh and < 200 kWh). The key recommendations (Table 8) gave specific emphasis to requirements around system design, installation and safety considerations for the consumer of energy storage technology. Table 8 summarises the status of efforts to address the recommendations that are discussed in detail below. Significant work has been carried out to address the priority safety issues and develop mitigation actions. A lot of work has been carried out under the guidance of the Storage Integrity Working Group (SIWG) that was established by the Clean Energy Council (CEC). The main activities of the Working Group have included the development of installation guides; training and accreditation; and, in cooperation with state and territory governments, industry engagement and implementation of the installation guide that is now mandatory for all 'battery endorsed' CEC accredited PV installers. The group has also contributed through EL042 to the development of new standards (AS 5139) and has advocated for a national register for energy storage systems. These initiatives are elaborated below.

Table 8. Summary of key findings and recommendations from Cavanagh, Behrens, et al. (2015) and current status of activities; findings and recommendations are numbered as they appeared in the original reference but they are aligned for consistency across the table rows to enable an assessment of current status

Findings (from (Cavanagh, Behrens, et al. 2015)	**Recommendations** (from (Cavanagh, Behrens, et al. 2015)	**Status update** based on this work
1. Lack of knowledge on the variety of storage technologies, how to use and operate them in a safe manner	1. Improve awareness and access to information on different technologies on appropriate use and operation for designers (engineers, electrical tradespeople), installers (electrical tradespeople) and consumers	CEC has developed installation guides and rolled out 'battery endorsement' for CEC accredited PV installers(CEC 2016) The ESC has also published 'The Australian Battery Guide' Guide for Energy Storage Systems (sales, design, installation and stewardship)(Cockburn 2016) NSW Dept of Industry is funding the development of consumer-facing resources to inform decision-making around energy storage technology with solar including safety management and installation
2. No consensus on how to extinguish a lithium battery storage fire	3. R&D to establish best method to extinguish lithium battery fire (in domestic/smaller commercial context)	Australian Standards HB 76 – 2010 Dangerous Goods - Initial Emergency Response Guide provides some information on how emergency response should respond A chemistry-specific response is required (the introduction of different chemistries poses significant risk) (Cockburn 2016)
3. Inadequate accreditation and training to support and provide training for designers and installers	6. Develop training and nationally recognized accreditation pathways for designers and installers	CEC and other organisations developing training, promoting industry knowledge sharing e.g. through regular industry forums Installation training course in draft developed by electro-technical IRC and we are aware of one utility that has instigated their own training course for electrical field staff
4. Limited training and support to educate emergency response teams (fire brigade, ambulance, police)		Stakeholders are looking to international experience, e.g. California Energy Storage Association, observing the potential to import a modified training course
5. Lack of standards for battery storage disposal and recycling	2. R&D to determine best recycling pathways and establish 'lithium-battery recycling initiative'	Batteries have been listed under the Product Stewardship Act with the expectation that industry will take the lead ABRI has developed safe transport, handling and recycling guidelines
6. Incomplete standards for battery storage installation	4. Align Australian and International standards and improve local regulatory and building codes for likely expanded applications of storage technologies	Standards Australia technical committee EL-042, Renewable Energy Power Supply Systems & Equipment, was expected to publish in Feb 2017 standard AS/NZS 5139, Safety of battery systems for use in inverter energy systems. However the timeline has been extended for further industry consultation

Findings (from (Cavanagh, Behrens, et al. 2015)	**Recommendations** (from (Cavanagh, Behrens, et al. 2015)	**Status update** based on this work
7. Energy storage installations and incidents are insufficiently reported	5. Establish a set of best practices and the development of installation, maintenance and incident reporting database	National Energy Storage register under consideration following industry consultation led by COAG Energy Council/ CBA currently under commission The importance of developing appropriate safety protocols for providing information for different stakeholders including signage with safety warnings and chemistry types was emphasised by government and industry stakeholders.

INSTALLATION GUIDES

The Clean Energy Council (CEC) developed installation guides given the absence of relevant and up-to-date Australian standards and to improve awareness and access to information on different storage technologies and system designs. The installation guide was first published in April 2016 and became a mandatory document for 'battery endorsed CEC accredited (PV) installers' on 1 October 2016. The purpose of the document was to 'provide interim guidance to designers and installers of grid-connected energy systems with battery storage systems, until new standards have been formalised'. The guidelines recommend safety measures and make reference to existing Australian and International Standards for batteries in buildings covering layout and arrangement, testing, commissioning, maintenance, and repair of battery banks but focused on lead-acid and/or alkaline (e.g. nickel cadmium) and/or focused on extra-low voltage for off-grid or standalone applications (i.e.: AS 2676, 3011, 4086, AS/NZS 4509) (CEC 2016).The Energy Storage Council (ESC) has also published 'The Australian Battery Guide' for Energy Storage Systems (sales, design, installation and stewardship) (Cockburn 2016).

Presently, CEC has an accreditation scheme for the installation of PV modules. For this scheme, industry engagement is enabled by a regulatory requirement for consumers to use a CEC-accredited installer to be eligible to claim rebates including renewable energy certificates (small-scale technology certificates [STCs]). Currently there is no accreditation scheme for batteries. In the absence of a standard and regulatory levers CEC advocate for the use of a 'battery endorsed' PV installer and have worked with state and territory governments to support this initiative, e.g. by making it a requirement for involvement in incentivised pilot schemes such as the ACT government's 'Next Generation Energy Storage Grants' (ACT Government 2016). Alternative approaches for engaging the industry to adhere to best safety management practice are discussed in Chapter 8.

STANDARDS

Owing to rapid developments in technology and new applications, current standards are either absent or out of date. A comprehensive overview of the standards that currently apply to lead-acid, lithium-ion, nickel and flow batteries was provided by Cavanagh et al. (2015). Specifically they reviewed Australian and international standards covering transport, handling, hazards, site location, system design, ventilation, cell, inverter, wiring/cabling, maintenance, signage, system documentation and end-of-life. This review enabled a 'gap analysis' that identified where standards were underdeveloped, out of date or missing between Australian and international standards across the different technologies. Reflecting on the likely technologies to be deployed in the Australian market in the near term, the following appraisal was made:

– Lead-acid: well established standards
– Nickel-based chemistries: well established standards
– Lithium-ion: In need of standards
– Flow: In need of relevant standards
– Sodium-ion: In need of relevant standards

This analysis has informed priority action focusing on the development of a new installation standard (AS 5139) that was expected to be published in Feb 2017 but the timeframe was recently extended for further industry consultation following controversy surrounding a leaked draft (Parkinson 2017c; Parkinson 2017a; Parkinson 2017b). This reflects a broader problem with the standards development process that has limited funding and relies on the efforts of committee members who are volunteers. Owing to the lack of resources, expert stakeholders involved in the process have expressed concerns about the timeliness of standards development, as well as the potential for parties with vested interests to bias the process. Details are provided regarding the status and priorities of ongoing standards development in Box 2.

BOX 2: Energy Storage Standards Roadmap

Standards Australia* in partnership with the COAG Energy Council undertook industry and government consultation to develop a roadmap for standards development (Standards Australia 2016b; Standards Australia 2016a; Standards Australia 2017).

Aligned with the work of CSIRO (Cavanagh, Behrens, et al. 2015), the industry and government consultation determined a scope which included grid-integrated and independent storage for residential and small-scale commercial batteries (acknowledging a need for different scales and technologies including sub-classes). The consultation process confirmed that *lithium-ion technology is the highest priority* for standards development.

Specific subject areas were also highlighted as priorities through this consultation process. These are listed below in order of priority with a brief summary of the current status:

Safety of installation standards. Standards Australia technical committee EL-042, Renewable Energy Power Supply Systems & Equipment, is currently drafting standard AS/NZS 5139, Safety of battery systems for use in inverter energy systems that was expected to be published in Feb 2017. The standard supersedes prior standards that only address off-grid systems. The hazards included are: electric shock hazard, energy hazard, fire hazard, chemical hazard and explosion hazard with mitigation actions covering earthing requirements, location of battery, signage and labelling, testing and commissioning. Notably dis-installation is not included

Product standards. These are evolving with rapid technology development and the consultation paper highlighted the importance of safety, quality as well as performance measurements under Australian conditions (e.g. high temperature). The importance of Australian engagement and support of International Standards development in this area was noted.

Grid connection standards. Two standards currently under development for publication:

(AS/NZS 4755.3.5 & AS 4777.1-2005)

Recycling, Handling and Transport. It was agreed that recycling be considered as distinct from handling and transport. There was a strong interest in recycling and product stewardship and it was acknowledged that the installation standards process could support recycling with appropriate labelling of battery technology that is within scope of AS/NZS 5139.

Recycling. Guidelines exist for lead-acid and nickel-based technologies. The Australian Battery Recycling Initiative in partnership with the CEC is leading conversations on best practice for the recycling of varied storage technologies.

Handling and Transport. A code of practice on Safety Data Sheets provided by Safe-Work Australia and given battery storage is classified as storage of dangerous goods, the Australian Dangerous Goods Code provides some guidance.

Training. The CEC and the Energy Storage Council and other groups such as Australian Industry Standards are currently developing training guidelines or accreditation programs for installers. It was considered that training needs are best supported through the publication of relevant standards, e.g. AS/NZS 5139.

International coordination. It was recommended that Australia should actively engage with the International Electrotechnical Commission (IEC) that has a relevant committee: IEC TC 120, Electrical Energy Storage System to align Australian standards work and interest with the work being done internationally.

* Standards Australia is the nation's peak standard body and Australia's representative to the IEC and ISO. Standards are written by members of technical committees comprising industry, government and university representatives. Australian Standards documents are voluntary when published but they can be called up in regulation.

NATIONAL ENERGY STORAGE REGISTER

The Energy Market Transformation Project Team (EMTPT) under the Council of Australian Governments' (COAG) Energy Council has conducted consultation on the need to collect and share information on battery energy storage through a national register (COAG Energy Council 2016).

Currently there are no requirements to register or report small-scale (< 5MW) behind-the-meter energy storage and there is some uncertainty around the number and scale of existing installations. It is noted that for larger scale energy storage, the Global Energy Storage Database (Australian Energy Storage Alliance n.d.) lists 39 operational projects in Australia with a capacity of 2.89GW that is almost entirely provided by PHES.

Subsequent to this consultation the COAG Energy Council has agreed 'in-principle' to develop a national register subject to a cost-benefit analysis that is underway (as of Feb 2017).

The consultation process helped to establish the rationale for a national register to protect the safety of consumers, line workers, installers and emergency response personnel as well as for power system and network security. Accurate and available data on installations, as well as reporting of safety incidents, is particularly important for safety risk management (such as fire risk management) and product recalls. It is also important for end-of-life management because it provides more accurate data on products reaching end-of-life (Crossley 2016).

What information and how it might be captured is yet to be established although the consultation found that information could potentially be available through connection agreements under the existing regulatory framework. The type of information involved includes: locations where battery energy storage has been installed; relevant systems parameters (e.g. chemistry type, system initial capacity in kWh, manufacturer model and serial numbers); status of installed system maintenance; and reports on safety incidents.

OTHER RECENT INITIATIVES

The CEC has established the Energy Storage Directorate and one of its first initiatives was to consider developing a product list for storage batteries. CEC currently maintains a database and website list of PV panels that comply with Australian standards and establishes a quality bar in terms of what products can be sold into the Australian market. The intention is to align with international product standards to avoid creating an additional barrier to entry for new manufacturers into the Australian market. Manufacturers providing products to Europe already adhere to product standards.

The NSW Department of Industry has sought quotes to develop consumer-facing resources (guides, fact sheets) to assist consumers with decision making on solar storage products. The scope of the work is intended to include safety and installation information.

4 Pumped Hydro Energy Storage

4.1 Technology overview

Pumped hydro energy storage (PHES) is the only technology already widely deployed for energy storage, making up 99% of installed storage capacity worldwide (Hearps et al. 2014; UNEP 2015). It is both efficient and low-cost. Current PHES facilities in Australia include the 600MW Tumut-3 and 240MW Shoalhaven facilities in New South Wales, and the 500MW Wivenhoe facility in Queensland (Hearps et al., 2014).

PHES systems are distinct from hydroelectric power, which are usually located in river valleys with huge reservoirs. PHES systems are smaller, comprised of two main reservoirs connected by pipes or tunnels. In times of excess energy, water is pumped from the lower to the upper reservoir, and is then released through a turbine to generate electricity during times of peak demand (Blakers 2015). PHES systems can be categorised by their water management as either closed loop, semi-open or open systems (stoRE 2014).

Historically, most PHES installed worldwide has been integrated with hydroelectric power stations on rivers, but there is unlikely to be any new hydroelectric power installed in Australia. There is however a large potential for off-river PHES in Australia. Off-river systems circulate the same water between reservoirs, so there is no need to be connected to a river. The remainder of this discussion focuses on off-river systems.

There are potentially thousands of sites for off-river systems in Australia, and studies have located potential sites that are outside of national park areas, such as hilly farming country. These sites are often located in similar landscapes to wind farms (Blakers 2015). Other research has found that there is potential to pump seawater to reservoirs on coastal cliff-tops (Hearps et al. 2014). Another innovative approach is to use closed mine sites as reservoirs. Genex Power is developing a 250 MW project in the site of the Kidston gold mine in northern Queensland, alongside a 330 MW solar farm (Genex Power n.d.).

The deployment of PHES may be limited by the difficulty of securing suitable sites, however it is considered of high potential due to its high efficiency, long lifetime and low costs (Banfield & Rayner 2016).

Table 9. Environmental and safety impacts for PHES

	Category	Impacts	Mitigation strategies
Environmental impact	Energy efficiency	Moderate-high round-trip efficiency of 75-80% (lower than Li-ion, similar to sodium-based or lead-acid batteries and higher than CAES) Likely longest lifetime of all technologies (acknowledging that water quality may impact on durability of components requiring significant maintenance)	Not a priority for further development of mitigation strategies
	Lifecycle GHG emissions	Lowest GHG emissions among the technologies for the infrastructure stage and for the whole lifecycle in a low-carbon energy mix, similar to Li-ion in a high carbon energy mix Potential GHG emissions associated with decay of biomass for reservoir creation	Prioritise development of PHES in existing modified areas
	Supply chain criticality	No materials used are considered critical	Not a priority
	Material intensity	Low material intensity Saltwater systems would likely have higher material intensities e.g. for corrosion resistant alloys	Not a priority
	Recyclability	Long life and low material use require minimal recycling Recycling pathways established for major material inputs (steel)	Recycling pathways not developed owing to immaturity of technology Reuse of membrane material not viable
	Environmental health	Large land footprint and potentially high water use, but have much less environmental impact that conventional hydroelectric power Closed loop systems have low water use, but do have some evaporative losses Water bodies are important for supporting biodiversity	Appropriate environmental impact assessment of potential sites PHES in existing modified areas where possible, locate outside of national parks or sensitive ecosystems Prioritise off-river, closed loop systems to minimise water use National strategic plan to identify and classify suitable sites
Social impact	Human rights	Potential land use conflict	Proper consent from land owners
	Health and safety	No major safety issues identified	Not a priority

4.2 Impacts

4.2.1 Energy efficiency

The round-trip efficiency of pumped hydro energy storage systems is moderate-high compared to alternative technologies, not as high as lithium-ion batteries but similar to lead-acid or sodium-based batteries. PHES systems compare favourably with other high-volume storage technologies such as CAES and hydrogen. The round trip efficiency is between 75% (Hearps et al., 2014) and 80% (Blakers, 2015; Oliveira et al., 2015).

The lifetime of a plant is the highest of all technologies, between 50 and 100 years (Blakers, 2015) up to 150 years (Oliveira et al., 2015). This gives an energy delivery over the lifetime that far exceeds all other technologies. Over the lifetime the plants will require repair and maintenance, particularly saltwater plants, e.g. owing to corrosion of components.

4.2.2 Greenhouse impacts

In considering the infrastructure impacts (including EOL), PHES systems perform the best of all the technologies compared by Oliveira et al (2015). Including the use phase, they are the best performer in a high renewable mix. With an energy mix with high carbon intensity, the impact of the infrastructure and use stage becomes similar (and slightly less favourable) to lithium-ion, as the use phase dominates the environmental impact of storage technologies. PHES has the lowest emissions of the high-volume bulk storage technologies.

Although detailed data is not available, the impacts in the construction phase can vary significantly depending on the surrounding environment and the quality of the water supply. Data is not available on saltwater systems but they are likely to have higher emissions than freshwater systems owing to the need for corrosion resistant steel alloys.

4.2.3 Supply chain criticality

None of the materials used for PHES systems are considered critical. The major materials are concrete, steel, aggregate and plastics.

4.2.4 Material intensity

Data is not available on the material intensity of PHES systems, however due long lifetime and high efficiency of PHES it is considered to have a low material intensity. Conventional hydroelectric systems have a lower material use per kWh compared to concentrated solar power (UNEP 2015). As discussed above, the repair and maintenance requirements over the lifetime are expected to be dependent on water quality and may be significant for saltwater plants.

4.2.5 Recyclability

As the lifetime of PHES is so long, recyclability becomes less important than for other technologies. Steel is a major component of PHES systems and it has established recycling pathways.

4.2.6 Environmental health

PHES have potential to adversely impact the health of local environments but the risks are considerably less than conventional large hydroelectric power plants. PHES systems have a large land footprint, and as with any large infrastructure project, there is potential to disturb local ecosystems (stoRE 2014). The small size of off-river reservoirs (around one hectare) minimises environmental impact.

Water is naturally essential for PHES systems, but water use is not a major concern as may be thought. Off-river closed-loop systems cycle water continuously through the system, so the only water use is through evaporative losses. This water use is tiny in comparison to that used in a coal fired power plant with the same output (Blakers 2015).

The environmental impacts from PHES systems can be minimal if adequate environmental management strategies are in place. These include conducting appropriate environmental impact assessments, particularly to understand any threatened species, and locating sites outside of national parks or other sensitive ecosystems. PHES should be located in areas that are already modified to minimise disruption, preferably with reservoirs that already exist (stoRE 2014). Closed-loop systems should also be favoured and designed to reduce evaporative losses. In order to implement these measures, a national strategic plan for PHES that identifies appropriate sites based on their environmental risk, as well as cost and network needs, could ensure minimal risk. A clear communication of the nature of off-river PHES will reduce potential social licence issues.

4.2.7 Human rights

As with all large-scale and high-volume storage technologies, there are potential conflicts over land use that could arise from new PHES development. Strategies to mitigate environmental impacts should also consider the economic, social and cultural impacts of PHES developments on local communities.

4.2.8 Health and safety

No safety issues have been identified, however as with any large infrastructure, workplace safety measures must be followed, which are well established for PHES as a mature technology.

5 Compressed Air Energy Storage

5.1 Technology overview

Compressed air energy storage (CAES) stores energy by compressing air into a storage vessel that can be an underground geological structure (e.g., cavern, aquifer, abandoned mine), aboveground vessels, or underwater vessels. When energy is needed the compressed air is heated and expanded in a turbine with the potential to provide significant electrical output (of the order of hundreds of MWs).

CAES technology is mature, with two deployments operating for decades in Huntorf Germany (1978) and Alabama USA (1991). Both plants use salt caverns and have demonstrated long-term reliable performance (Luo et al. 2015; Dresser-Rand n.d.). During the compression step the air heats up and must be cooled for storage; the air is then reheated for expansion. Heating is typically achieved by combusting some natural gas and heat can also be recuperated from the hot combustion exhaust gas from the gas turbine. Further thermal efficiencies can also be gained by storing the heat from the compression step and utilising this to reheat the air for expansion, thus eliminating the need for fossil fuel combustion. This is known as 'advanced adiabatic CAES' (AA CAES) and is a comparatively immature technology. Hydrostor Inc has been operating their Toronto Island plant in Toronto Canada since November 2015 incorporating underwater storage with plans to expand to multiple MWh storage capacity; another plant is under construction in Goodrich, Canada (Hydrostor n.d.). The company recently announced a partnership with AECOM to jointly develop Hydrostor's AA CAES with their proprietary underwater air cavity and/or underground approach (AECOM 2016). In Germany a demonstration plant is under development led by RWE Power (Energy Storage Association n.d.; RWE Power 2010). The project plans for a storage capacity of 360 MWh and an electrical output of 90 MW and is aiming for a 70% round-trip-efficiency.

This analysis is focused on the mature CAES with natural gas fuelled heating. Artificial caverns are favoured owing to good sealing and no reaction between oxygen and host rock. James and Hayward (2012) indicated very limited potential for underground CAES deployments in the NEM with only one storage site in the Adavale Basin in Queensland identified (a significant distance from the grid). Aside from salt caverns, other storage vessels have been investigated in the context of international research projects at pilot scales, e.g. see a review by (Luo et al. 2015; Luo et al. 2014).

Significant R&D is focused on moving the technology towards modular, scalable and above-ground applications as an alternative to batteries for industrial applications. The main advantage of aboveground vessels is the potential for installation anywhere on the electricity grid (Luo et al. 2015; Luo et al. 2014).

The environmental and safety impacts assessed in this chapter are summarised in Table 10.

Table 10. Environmental and safety impacts for CAES

	Category	Impact	Mitigation strategies
Environmental impact	Energy efficiency	Low round-trip-efficiency (40-55% range owing to varying degree of heat recuperation)	'Advanced adiabatic CAES (AA CAES)' is under development (TRL 4) with potential for increased thermal efficiencies
	Lifecycle GHG emissions	Heat input for reheating air for expansion typically achieved by combusting NG leads to CO_2 emissions Benchmarked against a conventional gas turbine with the same output, the potential emission saving are of the order of 40–60%	AA CAES eliminates NG combustion
	Supply chain criticality	Materials are not considered critical	Not a priority for further development of mitigation strategies

	Category	Impact	Mitigation strategies
	Material intensity	Material intensity is low compared to other storage technologies	Development of above-ground applications would likely lead to further improvements
	Recyclability	Long lifetimes ~ 40 years Recycling pathways established for major material inputs (aluminium, copper and iron)	Not a priority
	Environmental health	Lower impact on landscape compared to pumped hydro 'Brining' requires removal and processing of large volumes of salt water	Not a priority
Social impact	Human rights	Land-use impacts associated with large-scale technology	Not a priority
	Health and safety	Technology and components have close analogues in many commercial industrial processes e.g. turbines, pressure vessels, piping and fitting	Mature technology with well established operating protocols

5.2 Impacts

5.2.1 Energy efficiency

The need to cool and reheat the air for compression and expansion results in a low round-trip efficiency ranging from 40-55% (~ 20 percentage points lower than pumped hydro) depending on the level of heat integration. Heating is typically achieved by combusting some natural gas and heat can also be recuperated from the hot combustion exhaust gas from the gas turbine. Storing the heat from the compression step and utilising this to reheat the air for expansion – thus eliminating the need for fossil fuel combustion – can also gain thermal efficiencies.

The fuel load is one-third that of a conventional gas turbine for the same output, the ramp rate is faster and the part-load efficiency is higher because the air is already compressed (James & Hayward 2012).

As discussed above, 'advanced adiabatic CAES' achieves further thermal efficiencies by storing the heat from the compression step and utilising this to reheat the air for expansion, thus eliminating the need for fossil fuel combustion. This technology remains under development.

5.2.2 Greenhouse impacts

For conventional CAES, the heat input for reheating air for expansion is typically achieved by combusting natural gas and this leads to CO_2 emissions. However, benchmarked against a conventional gas turbine with the same output, the potential emission saving are of the order of 40–60 % depending on utilisation of waste heat by offsetting fuel utilisation (Energy Storage Association 2016).

5.2.3 Material intensity

The relative material intensity of CAES is considered very low given that the material intensity of natural gas power plants is lower than all renewable energy technologies (CSP > hydro > wind > PV) based on the mass of major inputs (aluminium, copper, iron and cement) per energy output. This is a conservative comparison given CAES is more energy efficient than conventional natural gas power plants (UNEP 2015).

5.2.4 Recyclability

The expected lifetime of CAES plants are about 40 years and there are recycling pathways for the major material inputs (aluminium, copper, iron and cement).

5.2.5 Environmental health

In terms of land-use there is lower visible impact on landscape but the process of forming salt caverns (called ‘brining’) involves the removal and processing of large volumes of salt water.

5.2.6 Health and safety

Despite limited deployments the technology and components have close analogues in many commercial industrial processes e.g. turbines, pressure vessels, piping, and fittings. On this basis the mitigation strategies to address the safety concerns associated with CAES may be considered well established.

Owing to the limited potential for deployment in Australia and the relative maturity of the CAES technology, the development of policy to mitigate environmental and safety issues is not a priority.

6 Hydrogen Energy Storage

6.1 Technology overview

Hydrogen energy storage refers to an integrated suite of technologies (Table 7) from production to end-use that exploits the versatility of hydrogen as an energy carrier and/or chemical feedstock. H_2 production in the context of this study involves the conversion of (surplus) renewable electricity into H_2 by water electrolysis. In this process, an electric current is used to split water into H_2 and O_2. Hydrogen energy storage is attractive for bulk storage, along with pumped-hydro and compressed air energy storage, as well as renewable energy export. In these contexts, the key benefits are (Decourt et al. 2014):

- the potential for long-term bulk energy storage (> weeks)
- the opportunity to leverage existing gas infrastructure, both gas transport and end-use technologies (turbines)
- unique flexibility with regards to end-use, i.e. H_2 can be used to generate electricity, directly as a transport fuel, indirectly as a feedstock for synthetic fuels, and a feedstock for industrial processes. This flexibility in terms of end-use allows H_2 to play a role in decarbonising heat, power, transport and industrial end-uses.

The technologies are categorised according to five main steps: H_2 production, conditioning, storage, transport and end-use as shown in Figure 1. These are discussed below.

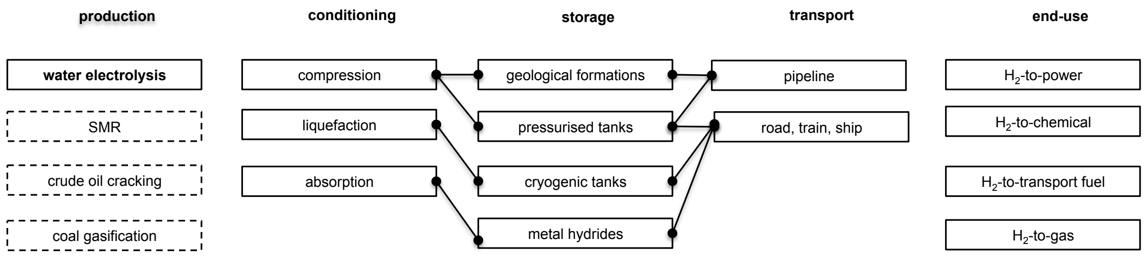

Figure 1: Overview of the range of potential technology pathways that characterise hydrogen energy storage

Production

There are three main water electrolysis technologies: alkaline systems, proton exchange membranes (PEM) and solid oxide electrolyser cells (SOEC). Despite the technical maturity and cost-efficiency of continuous alkaline systems for water electrolysis, for our appraisal of the environmental and safety impacts we consider PEMs as the likely technology for H_2 production for storage applications. PEMs allow flexibility in terms of being able to respond to variable electricity loads and major technology developers (e.g., Siemens) are backing the development of this technology. PEMS can also deliver self-pressurised H_2 to end-users. SOECs remain under development at laboratory scales (Decourt et al. 2014).

Conditioning

The main technologies are compression, liquefaction and absorption. Conditioning is considered a technically mature step owing to hydrogen utilisation in the chemicals and petrochemicals industries.

Storage

Pressurised tanks are likely to be the main way of storing H_2 for small-to-medium scales (0.1-10 MWh) and high cycling rates. Owing to industrial experience, pressurised tank storage is considered safe and cost-efficient. For larger scale storage applications, geological storage is likely to be the most viable, but this is immature and limited by geologies.

Transport

The main transport options are by vehicles, vessels and pipelines. Road transport with compressed H_2 tanks enables distributed delivery but is limited to relatively short distances and volumes. Pipelines are generally considered the lowest-cost option for large volumes that can include injection into existing natural gas distribution infrastructure at low concentrations. Liquid hydrogen and ammonia are applicable for transport at large volumes over the large distances usually associated with export.

End-use

Four main end-use options are examined: H_2-to-power can involve the use of fuel cells or combustion turbines, but only the latter are considered in the context of this work. Power-to-(H_2) gas integrates power and gas grids, effectively enabling the use of existing gas network infrastructure to store renewable energy with the additional benefit of potentially decarbonising the end-use (e.g. heat, power, transport fuel, chemical feedstock). H_2-to-fuel involves a number of pathways involving the synthesis of carbon fuels from hydrogen by reaction with a carbon source. H_2-to-chemicals includes a range of mature industrial applications including the upgrading of crude oil and ammonia production. The latter is also considered as a possible pathway for targeting export markets.

This evaluation considers the environmental and safety issues and impacts across these main steps. A summary of the environmental safety impacts is provided in below.

6.2 Impacts

6.2.1 Energy efficiency

Considering H_2-to-power utilising mature combustion turbine technology, on a round-trip-efficiency basis hydrogen energy storage is not competitive with other storage technologies. Accounting for the energy penalty associated with electrolysis, conditioning, storage and re-electrification, a round-trip efficiency of about 20% was reported. Higher round-trip efficiencies approaching 50% are anticipated assuming significant technology development across the supply chain (Decourt et al. 2014).

Owing to the very low energy density of H_2, the conditioning step (e.g. compression, liquefaction or absorption) is important and energy intensive. The energy losses for this step range from 5–45% depending on the technology that is required for integration with the transport and storage route.

The main technologies for H_2-to-power are fuel cells and combustion turbines. Because fuel cells are predominantly under development for transport applications, this is not a major focus for this study. The most technically mature H_2-to-power pathway involves combustion turbines operating with CH_4 and H_2 blends; mixes with up to 5 vol % H_2 is considered to be usable without modification. (Pure H_2 turbines remain under development and are not considered within the scope of this research.) The thermal efficiency of the conversion of H_2 to electricity can be 60% assuming combined cycle gas turbines technology (Decourt et al. 2014).

For niche large-scale, long-distance (and long-duration) energy export applications (e.g. based on H_2-to-ammonia), efficiency estimates should consider the whole lifecycle and end-use. In general there is a strong research agenda focused on efficiency improvements to electrolysis technology. Considering the conversion of H_2-to-ammonia for large-scale transport to export markets, there is a strong research agenda targeting efficiency improvements through process intensification, e.g. by integrating air separation with ammonia productions.

Table 11: Environmental and social impacts of hydrogen energy storage pathways

	Category	Impact	Mitigation strategies
Environmental impact	Energy efficiency	Low round-trip efficiency for re-electrification Application for large-scale energy storage and transport to export markets	R&D agenda improving energy efficiency electrolysis, process intensification (upstream) for ammonia pathway
	Lifecycle GHG emissions	Dependent on electricity production, electricity from wind has lowest impact H_2 is a tropospheric ozone Potential to decarbonise end-use	Pathways depend on broader energy, transport and climate policy Carbon-based fuels could use CO_2 captured from air
	Supply chain criticality	Scarcity of platinum catalysts for PEM	Reducing demand through dematerialisation, catalyst longevity and substitution to potentially reduce demand
	Material intensity	Platinum Utilise existing gas and/or ammonia infrastructure	Strategic policy supporting infrastructure development
	Recyclability	Recycling technology enables recovery of platinum catalysts	Recycling pathways not developed owing to immaturity of technology Reuse of membrane material not viable
	Environmental health	Platinum extraction Water as feedstock Small land footprint (electrolysis) Low acidification potential Risk of eutrophication (NH_3)	Lots of R&D into using saltwater Further R&D required to understand impact of large leakage of H_2 to environment
Social impact	Human rights	Potential land use issues	Proper consent from land owners
	Health and safety	H_2 flammability Damage internal structure of materials Leaks are hard to detect Potential exposure risk in manufacturing for platinum recovery	Risk mitigation well established in industrial context Sensor technology not practical for deployment For ammonia pathway there are already codes, procedures and equipment in place for handling, transport and storage in Australia There is a paucity of data to inform the development of safety systems and policy.

6.2.2 Greenhouse impacts

Electrolysis conversion does not generate direct emissions but there are lifecycle emissions dependent on how the electricity is generated and from manufacturing the electrolyser cells and decommissioning at end-of-life. However, electrolysis hydrogen storage likely has lower emissions than other energy storage technologies (Decourt et al. 2014; Bhandari et al. 2014).

Bhandari et al. (2014) appraise the lifecycle impacts of H_2 production via electrolysis based on a review of 21 published lifecycle assessment studies. The lifecycle emissions (not including end-use) are most dependent on the electricity production used for electrolysis. The contributions from the electrolyser unit (including manufacturing and decommissions) was reported to be relatively small, e.g. the contribution to the global warming potential (kg-CO_2 eq /kg H_2) for wind-based electrolysis was 4%. Their study concluded that electrolytic hydrogen produced by wind and hydropower had the lowest emissions and this is consistent with other analyses, e.g. (Decourt et al. 2014).

Considering different end-uses the power-to-gas pathway that integrates power and gas distribution infrastructure effectively enables the use of the (existing) gas network to store renewable energy. In general the injection of 1–5% H_2 into the gas network is viable with no modifications. Higher concentrations are tolerable up to 20% in the distribution pipelines, however modifications are likely required downstream e.g. for gas combustion turbines (Decourt et al. 2014).

A number of synthetic fuels, e.g. methanol, dimethyl ether, synthetic diesel, can be synthesised from H_2 by reaction with a carbon source. Methanol is thought to be the most promising and the carbon may be sourced from CO_2 or CO. These processes require the input of large volumes of CO_2 that can be sourced from industrial exhaust gases using carbon capture technologies; however, these technologies are currently not widely deployed and the subsequent combustion of synthetic fuels leads to the (re-)release of CO_2 to the atmosphere, undermining mitigation efforts. In theory, CO_2 can be captured from air but the relatively low concentrations of CO_2 in air (compared to flue gas) currently limit this technology to niche applications including biomass energy coupled with carbon capture, e.g. (Global CCS Institute 2016).

H_2 combined with nitrogen (from air) to produce ammonia is also under development and represents a move away from carbon-based fuels and appears to be a promising future pathway for exporting renewable energy and decarbonising end-use markets. Ammonia can be used directly as a fuel or cracked back to H_2. Currently, more than half of the H_2 produced worldwide is used for ammonia production but there are no examples of operating projects whereby electrolytic H_2 is used as the input (e.g. (Decourt et al. 2014). The economic efficiency of transportation of hydrogen-dense ammonia (compared to the alternative large volume transportation options, i.e. liquefaction) could be a driver for electrolytic hydrogen, particularly in remote locations e.g. in Western Australia where ammonia manufacturing is already established (Yara Pilbara n.d.).

6.2.3 Criticality

Considering PEM technology for H_2 production for storage applications, this technology uses noble metal catalysts (platinum, iridium, rhodium) that are identified as critical materials on the basis of supply chain constraints (Graedel et al. 2015).

In light of their high costs and potential supply chain constraints there is a significant R&D agenda focused on reducing material input, increasing catalyst longevity and substitution to potentially reduce demand (Ellingsen et al. 2016).

6.2.4 Material intensity

In general PEM for electrolysis uses the same materials and manufacturing (i.e., membranes, catalysts and catalysts synthesis techniques) as PEM fuel cell applications (Grigoriev et al. 2006). As discussed above, platinum catalysts are costly and scarce, and can degrade owing to poisoning from impurities requiring more platinum extraction. For these reasons there is significant research effort aimed at minimising or eliminating platinum use (Ellingsen et al. 2016).

Considering the overall technology chain, there is good potential for material and infrastructure use efficiencies because of the option of injecting H_2 directly into existing gas distribution infrastructure with minimal modifications (assuming low concentrations < 5 vol %); and, the opportunity to utilise existing ammonia distribution infrastructure may also present opportunities for shared infrastructure utilisation.

6.2.5 Recyclability

This appraisal of recyclability considers PEM water electrolysis technology. Dissimilar to distributed battery technology, PEM technology would likely be deployed at industrial scales such that the reverse-logistical challenges for material recovery are less problematic. There are different pathways for platinum catalyst recycling including gas phase volatilisation, hydrometallurgical and pyrometallurgical processes developed in the context of recovering platinum from automotive catalytic converters and e-waste (Ellingsen et al. 2016). In general efficient recovery is achievable enabling the reuse of the catalysts. Large-scale metallurgical operations currently operate in Europe, e.g. Umicore's integrated smelter-refinery in Belgium Assuming. Assuming the scrap containing platinum group metals reaches the recycling facility a recovery efficiency of 95% is achievable (Hagelüken 2012). Separation of membranes from catalysts layers is difficult and so reuse of the membrane material is currently unviable (Ellingsen et al. 2016).

6.2.6 Environmental health

The main factors identified that impact environmental health are land footprint, water usage, acidification, H_2 leakage, and eutrophication. In terms of the land footprint, best estimates for electrolysing modules are based on commercial facilities, indicating a relatively small land footprint compared to other bulk energy storage technologies (CAES and pumped hydro). Given water is a feedstock (e.g. ~ 250–560 litres estimated per MWh [Decourt et al. 2014]) this is an important factor for consideration in dry areas. Whilst it is technically possible to use salt water and the presence of salt is not the main challenge, the presence of biotic impurities would likely require additional purification steps and further research is required to advance this option. In terms of non-CO_2 gaseous emissions, LCA analyses indicate a low acidification potential (associated with SO_2 emissions) for wind and solar electrolytic H_2 (Bhandari et al. 2014). However, should H_2 energy storage become an important technology, further research is required to better understand the impact of releasing large quantities of H_2 into the atmosphere. H_2 is a tropospheric ozone precursor, although the potential contribution to global warming in the event of H_2 leakage is considered negligible (Derwent et al. 2006). Finally, considering the H_2-to ammonia pathway the only environmental impact may be eutrophication.

6.2.7 Health and safety

In terms of general risks (Decourt et al. 2014; Ellingsen et al. 2016):

- H_2 is flammable and potentially explosive over a wide range of concentrations and a relatively small amount of energy is required for ignition. However, in well ventilated areas H_2 quickly dilutes to non-flammable concentrations. Moreover, whilst the flame is as hot as a hydrocarbon flame, the flame radiates less heat and this limits the potential for secondary fires.
- H_2 molecules are small and light and can pass through/into materials and potentially damage internal structures by different physical and chemical mechanisms. Specifically, the embrittlement of steels and alloys resulting from exposure to H_2 gas may create internal defects (blistering, cracking, chemical attack) with the potential to lead to leaks.
- Leaks are hard to detect owing to the colourless and odourless nature of H_2 with sensor technology that is used in laboratories not yet practical for widescale deployment.
- At end of life, gas phase volatilisation for platinum recovery involves use of chlorine gas posing potential exposure risk to workers.

While acknowledging these risks, the core technologies developed for hydrogen energy storage are relatively mature, many of the steps are already deployed at scale for industrial applications, and there are well-established management and mitigation strategies. In these contexts handling is restricted to trained workers, limiting exposure to safety risks.

Production with PEM water hydrolysis is a mature technology. Similarly, the main technologies for conditioning are considered technically mature owing to experience of H_2 utilisation in the chemical and petrochemical industries. In regard to storage, if pressurised tanks are used then there is the risk of high-pressure explosions; for larger-scale storage in geological formations, salt caverns are considered the safest option while knowledge of other geologies (deep aquifers and depleted oil and gas fields) remains immature. There is lots of experience with natural gas storage in geological formations but H_2 is more mobile and so it has a greater potential to leak. Thus, further research is required to better characterise transport mechanisms and interactions between H_2 and host rocks (i.e. H_2 is small and light meaning that the molecule is mobile and can pass through/into other materials and react with material components). In general, leaks are hard to detect and there is a need to develop sensor technology for deployment in the field (Decourt et al. 2014). Considering the H_2-to-ammonia pathway, ammonia transport and handling is well established in the context of the fertiliser industry with established safety and risk management procedures.

The wide deployment of hydrogen storage (across the range of potential pathways) would necessitate significant work to develop specific codes, standards and regulations. Given the range of potential end uses, which might include a variety of small-scale end uses, significant effort would be required to harmonise tailored policy approaches to manage the risks. Owing to the immaturity of hydrogen energy storage there is a paucity of data concerning hydrogen safety. To address this lack there are a number off international initiatives to consolidate and disseminate hydrogen safety information, for example the International Association for Hydrogen Safety, HySafe (2004-2009), that had the mission to be “the focal point for hydrogen safety research, education and training” (HySafe n.d.). One of the activities of HySafe was the development of the Hydrogen Incident and Accident Database (HIAD). The HIAD website is hosted at the European Commission Joint Research Centre’s Online Data and Information Network for Energy (ODIN) portal (EC JRC n.d.). The database is a repository for information on accidents and incidents related to production, transport, supply and commercial use. After the closure of HySafe in 2009, the International Association for Hydrogen Safety (IA HySafe), a new legal entity that is a not-for-profit, was founded to continue activities such as HIAD, and to host the bi-annual International Conference on Hydrogen Safety.

Information on the existing codes and standards for hydrogen is maintained by the American National Standards Institute (ANSI). Whilst some codes and standards exist there is a strong need to address the growing range of applications. For example there are standards for hydrogen separation from water and the use of hydrogen gas to generate electricity for industrial and residential generators (ISO 22734-1:2008 Hydrogen generators using electrolysis process: Part 1: Industrial and commercial applications; ISO 22734-2:2011 Hydrogen generators using electrolysis process: Part 2 Residential applications) The first pages of the documents can be viewed for free from the ANSI website (ANSI n.d.).

7 Concentrated Solar Power with Thermal Energy Storage

7.1 Technology overview

Concentrated solar power (CSP) technology is unique compared to variable renewable energy technologies as CSP plants are typically integrated with thermal energy storage and can provide ‘dispatchable’ clean energy. CSP can also produce high-temperature heat that can be used for industrial processes.

CSP uses mirrors or reflective lenses to concentrate sunlight onto a receiver and then convert the sunlight to electricity, typically by using a heat transfer fluid (e.g. thermal oils) to transfer the energy to a central power system. There is a range of approaches for the conversion of solar energy to power, including photovoltaics, although most CSP systems use conventional steam turbines. Most CSP systems have been developed as standalone power plants. However, the use of conventional steam turbines enables integration with existing fossil plants whereby some of the steam produced by combusting fossil fuels can be displaced by heat from the CSP plant There are five plant variants: trough, linear Fresnel, dish, tower and Fresnel lens. Trough technology is the most commercially mature although deployment of CSP remains at an early stage, with the first commercial plants built in the 1980s without energy storage. Further details around the different technologies is available in the literature, e.g. (Lovegrove et al. 2012; IEA-ETSAP and IRENA 2013)

There are three broad categories for thermal energy storage: sensible, latent and thermochemical. In sensible heat storage, the storage (and release) is based on the temperature difference of the storage material. In latent heat storage, the storage material undergoes a phase change and a much higher energy storage density can be achieved by exploiting the enthalpy of the phase change. Finally, thermochemical heat storage involves exploiting a reversible chemical reaction between two materials where by thermal energy is stored by driving an endothermic chemical reaction (Klein & Rubin 2013).

There is a significant research agenda focussed on the development of small scale CSP (from 100 kW up to 1 MW) for heating and cooling in buildings, industrial process heat and rural on/off grid applications. For example, researchers from the University of South Australia were recipients of the ANSTO Eureka Prize for the development of phase change materials targeting applications for energy storage integrated with home refrigeration and air-conditioning. This technology has been demonstrated at commercial scale however the use with solar power plants is the focus of future research. Sensible heat storage is the most mature thermal storage technology and it is deployed at commercial scales using a two-tank molten nitrate salt system (composition 60 % $NaNO_3$, 40 % KNO_3). The molten salts are cycled between a cold tank (~ 300 °C) and a hot tank (~ 400 °C) and this enables 3–12 hour storage capacity.

This evaluation of the environmental and safety impacts only considers molten (nitrate) salt systems owing to their technical maturity and likely deployment within the timeframe of interest for this study (Lovegrove et al. 2012; Hinkley et al. 2013).

Table 12: Environmental and social impacts of CSP with TES

	Category	Impacts	Mitigation strategies
Environmental impact	Energy efficiency	CSP TES achieves a relatively high efficiency because it involves fewer energy conversion steps compared to wind or PV coupled to a storage technology The thermal efficiency is limited by the peak steam temperature, as well as the capability of storage materials to withstand higher working temperatures without decomposing	There is an R&D agenda that is focused on developing advanced storage materials/HTF (e.g. super-critical CO_2, thermochemical energy storage) targeting efficiency improvements and smaller scale operation
	Lifecycle GHG emissions	Emissions of CSP with TES back-up are lower than CSP with fossil back-up; operating and maintenance account for the largest share Storage contributes about 1/5 to the total the GHG from manufacture and construction (cradle to-gate) (~5 /25 kg-CO_{2eq}/MWh)	Not a priority for further development of mitigation strategies
	Supply chain criticality	Potential constraints apply to the CSP system, i.e., the supply of silver (used for the reflectors) and the 'silvering' process uses cerium that is a rare earth metal with limited supply pathways and few substitutes	Not a priority
	Material intensity	Relatively high major material requirements for CSP system compared to other renewable energy technology (however the material intensity should be considered relative to wind/solar coupled with batteries) Molten (nitrate) salts are cheap and abundant, with low degradation rates (< 0.5 % pa)	Not a priority
	Recyclability	Relatively long lifetimes of CSP TES (compared to batteries) ~ 30 years Molten salts have slow rates of degradation	Salts can theoretically be used as fertiliser at end-of-life. Whilst current recycling of CSP reflectors is limited there are established recycling pathways for the major material inputs.
	Environmental health	Environmental impact associated with high material intensity, significant water usage (that can be minimised with dry-cooling) The land footprint is relatively large but deployment in desert where land-use may be less of a constraint	Not a priority
Social impact	Human rights	Land-use impacts associated with large- scale technology	Not a priority
	Health and safety	Mature technology with well established operating protocols for safe high temperature operations Nitrate salts are non-toxic	Not a priority

7.2 Impacts

7.2.1 Energy efficiency

CSP TES achieves a relatively high thermal efficiency because it involves fewer energy conversion steps compared to wind or PV generation coupled to a storage technology. The peak steam temperature, as well as the capability of storage materials to withstand higher working temperatures without decomposing or degrading, limit the overall thermal efficiency of conventional CSP integrated with standard steam turbines. In the context of fossil-fuel generation, the development of supercritical and ultra-supercritical (steam conditions 30 MPa, 600 °C) steam cycles has led to significant efficiency gains. Early CSP systems used thermal oils that decomposed at ~ 400 °C. This was found to be incompatible with more efficient steam cycles and led to an interest in molten salts as well as other heat transfer fluids (e.g. supercritical CO_2). Improving the thermal efficiency of the steam cycle offers important cost efficiencies because it reduces the amount of thermal energy that needs to be collected for the same electricity output and thus, it reduces the size and cost of the solar field (Hinkley et al. 2013). Improved steam cycle efficiency is also expected to reduce water consumption.

7.2.2 Greenhouse impacts

It is difficult to directly compare CSP with TES in terms lifecycle emissions because these systems generate electricity as well as provide energy storage. The operational stage is often the main contributor to lifecycle emissions, for example those attributed to indirect emissions from auxiliary electricity use. Direct emissions from back-up fossil fuels (natural gas) was the major contributor to operating emissions for a CSP plant with 6 hour TES under the modelling assumptions and boundary conditions applied by Klein and Rubin (2013). However, a plant with an NG-fired heat transfer fluid heater for energy storage had 4–9 times the lifecycle emissions of the plant with TES. In terms of the contributions to the manufacturing and construction lifecycle emissions, the TES only contributed about 20% (i.e. cradle-to gate; ~ 5 $kgCO_{2eq}$/MWh)(Klein & Rubin 2013).

7.2.3 Criticality

There are no issues in terms of material criticality of the TES materials. For the CSP system, there are potential constraints on the supply of silver (used for the reflectors) under high renewable energy deployment scenarios and the 'silvering' process in which successive layers of silver are deposited uses cerium. Cerium is a rare earth metal supplied mostly from China and it is not easily substituted (Teske et al. 2016).

7.2.4 Material intensity

As discussed above in the context of lifecycle GHG, it is difficult to make a direct comparison with other storage technologies and so material intensity might be more reasonably considered relative to PV with battery storage. In terms of molten nitrate salt storage (that is assumed to be the dominant TES for the timeframe of this study) using sodium and potassium nitrates (60% $NaNO_3$, 40 % KNO_3) – these salts are abundant and non-toxic and the degradation rate is low such that there is minimal need to input of fresh materials over the long lifetime of the plant. Considering, the CSP systems (particularly tower technology), they have relatively high major material requirements (Al, Cu, Fe and cement) compared to other renewable energy technology, and silver is also required for the reflectors (Hertwich et al. 2014).

7.2.5 Recyclability

As previously mentioned, CSP with TES have relatively long lifetimes (~ 30 years) (Klein & Rubin 2013) and the rate of degradation of molten salts is very slow (< 0.5 % pa) such that there is minimal need to input fresh materials. In theory, these materials can be used as fertiliser at end-of-life (Klein & Rubin 2013). Current recycling of CSP reflectors is limited owing to the maturity of the technology and the long lifetimes. However there are established pathways for the major metal inputs.

7.2.6 Environmental health

The environmental impacts are associated with the relatively high material intensity, and relatively large water demand because the CSP with TES needs water to cool and condense the steam. Compared to conventional fossil-fuel plants, CSP systems typically consume more water on-site per unit of electricity generated owing to the less efficient steam cycle (as discussed above) although significant reductions on the lifecycle water consumption can be achieved with dry-cooling (~ 70–80% reduction) (Turchi et al. 2010; Klein & Rubin 2013).

A relatively large land area is required for the solar field for CSP but there is good scope for deployment in desert environments where land-use may be less of a constraint (Pfenninger & Gauché 2014).

7.2.7 Health and safety

CSP TES is a relatively mature technology with well-established operating protocols for safe high-temperature operations.

8 Discussion and Key Findings

8.1 Risk matrix comparing impacts across technologies

Table 13 below provides an overview of the environmental and safety impact ratings across the storage technologies. Whilst it is difficult to make a direct comparison across the technology groups (owing to different technology characteristics, technical maturities, and potential applications at different scales) this comparison is useful to flag impact ‘hot spots’, inform a future research agenda, and support the development of priority mitigation and management strategies.

Considering the energy efficiency and lifecycle GHG emission criteria, the analysis shows that the dominant lithium-ion battery chemistries (NMC, LFP), pumped-hydro and CSP with TES perform well compared to the other technologies.

For material intensity and recyclability, the potential for adverse environmental impacts associated with material use of batteries is greatest, with the exception of lead-acid batteries for which ULAB recycling is mature. Conversely, this highlights the opportunity to develop recycling technologies for other battery technologies. The supply chain criticality for the NMC chemistry is highlighted owing to the use of cobalt (graphite and lithium) that is supplied exclusively from the DRC.

Impacts on local environmental health are also most significant for the battery technologies (largely associated with the material intensity). Whilst the potential for adverse environmental impacts are also flagged for PHES, it is assumed that the management and mitigation strategies for PHES are easier to implement as they occur in Australia as opposed to offshore jurisdictions. Highest order adverse social impacts are also identified for the battery technologies due to the significant impacts associated with the mining and manufacturing that occur offshore in jurisdictions with poor human rights and health and safety standards. The fire risk of the lithium-ion chemistries is also flagged as an impact ‘hot-spot’ with mitigation and management strategies under development and new technologies (including alternative Li-ion chemistries such as LFP) actively being sought for large-scale energy storage

Table 13. Risk matrix comparing the ‘order’ (low-medium-high) of environmental and safety impacts across the storage technologies

High / Medium / Low

		Li-ion NMC	Li-ion LFP	Lead-based	Flow batteries	Sodium-ion	PHES	CAES	Hydrogen	CSP with TES
Environmental Impact	Lifetime energy efficiency	Low	Low	Medium	Medium	Medium	Low	Medium	Medium	Low
	Lifecycle GHG emissions	Low	Low	Medium	Medium	Medium	Low	High	Medium	Low
	Supply chain criticality	High	Medium	Low	Medium	Low	Low	Low	Medium	Medium
	Material intensity	Medium	Medium	Low	Medium	Low	Low	Low	Low	Low
	Recyclability	Medium	Medium	Low	Medium	Medium	Low	Low	Low	Low
	Environmental health	Medium	Medium	Medium	Low	Low	Medium	Low	Low	Low
Social Impact	Human rights	High	Medium	Low	Low	Low	Low	Low	Low	Low
	Health & safety	High	Medium	Medium	Low	Low	Low	Low	Medium	Low
	Overall	High	Medium	Medium	Low	Low	Low	Medium	Medium	Low

8.1.1 High-level risk analysis

To evaluate the risks and justify a priority focus for mitigation and management, the relative frequency and exposure ratings for the different technologies is presented in a quadrant diagram in Figure 2. Here, the colour of the box aligns with the overall impact rating shown in Table 13. The vertical axis provides a range of likely deployments from niche and/or exclusively utility scale to broad domestic deployment, and is a proxy for level of exposure (i.e. more stakeholders are exposed for technologies likely deployed in residential and small commercial markets). The horizontal axis provides a range of likelihoods of deployment consistent with the scenario modelling and techno-economics in WP1; it may be viewed as a proxy for frequency. Therefore, those technologies clustered towards the top-right quadrant represent the greatest risk and justify a priority focus for mitigation and management on battery technologies, particularly lithium-ion.

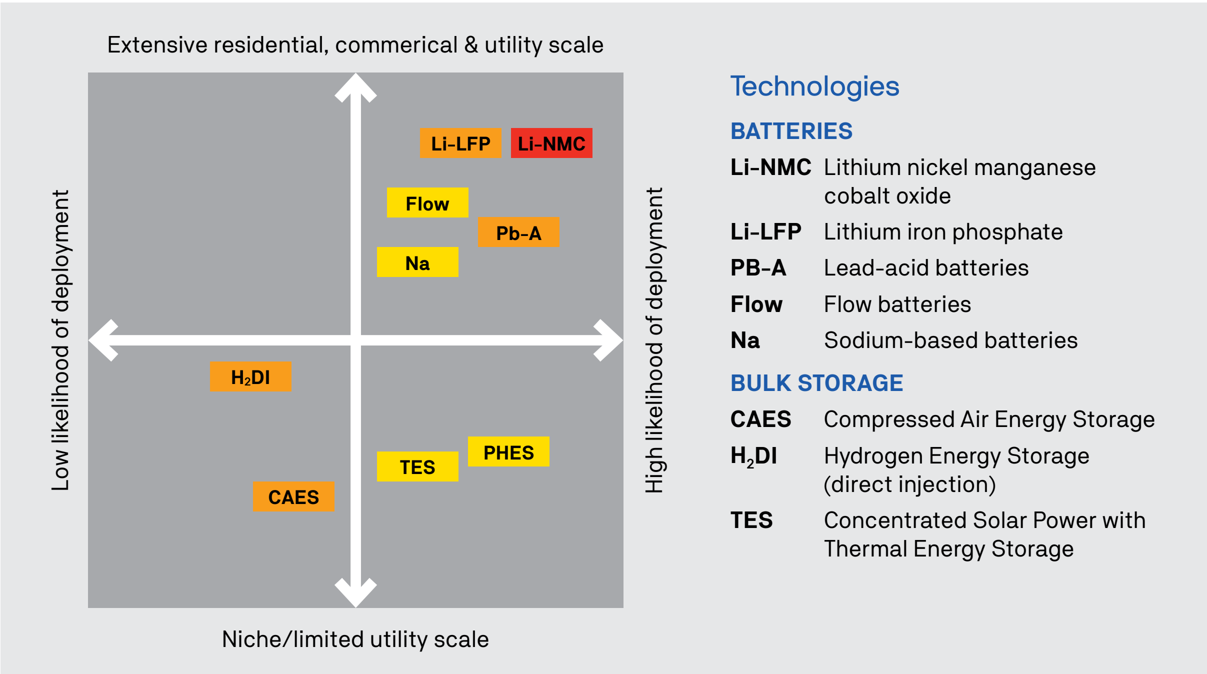

Figure 2. Quadrant diagram showing relative risk and exposure ratings for the energy storage technologies

8.2 Priority interventions

Based on the results from the environmental and safety impact assessments presented in Chapters 3–7, this chapter reflects on key findings and discusses priority policy interventions to mitigate the potential for adverse impacts.

This risk assessment reconfirms the focus on Li-ion technology for risk mitigation. The priority focal points for intervention are:

1. encouraging sustainable supply chains for metals
2. engaging the emerging battery energy storage industry to ensure the safety of all stakeholders
3. driving investment in responsible end-of-life management.

The range of current and potential future interventions that are pertinent to these focal points are identified and located on the supply chain to better understand:

Who are the relevant stakeholders?

What are their roles and responsibilities?

When are the critical timeframes for intervention?

Where are the synergies between policy interventions?

And, where is their applicable insight and experience from other policy approaches?

8.2.1 Intervention points for safety

Across the whole supply chain, safety risks were identified which impact stakeholders including transport workers, installers, consumers, first responders and recyclers (Figure 3).

The current focus of safety risk mitigation strategies prioritise installation, which makes sense in light of status of this emerging new industry for battery energy storage. As described in detail in Chapter 3 the main initiatives are: the development of installation guides, the development of installation standards, efforts towards establishing a National Energy Storage Register, and efforts to align Australian initiatives with international product standards.

How to engage the industry?

Presently, the key challenge is engaging with the industry to adopt best practice as standard development evolves and in the absence of any regulatory levers. In the absence of a mandatory installation standard and a nationally recognised training and accreditation pathway, the CEC has implemented 'battery endorsement' for its accredited PV installers. The CEC accreditation scheme for the installation of PV modules is touted as a successful approach that has supported the development the PV industry, fostering continuous industry learning and safe practice. Accreditation gives installers access to technical support and continuous professional development. Two accreditation pathways are available (design and design and install for standalone and grid-connected systems) with renewal specifications to ensure that installers keep up to date with industry developments. In this case, industry engagement was established on the basis that solar PV installations were only eligible for government rebates such as the Small-scale Technology Certificates (STCs) and feed-in tariffs if the installer was accredited with the CEC. To become 'battery endorsed' to install grid-connected battery storage design and install of grid-connected PV systems, accreditation is required and installers are required to complete additional training modules (the draft training codes are UEERE4002A and UEERE5001A covering design, installation, maintenance, fault finding for battery storage systems with grid-connected PV). The CEC has developed guidelines and 'battery endorsed' accredited installers are obliged to adhere to these (CEC n.d.).

The leverage for uptake by the industry is tenuous in the absence of any regulatory authority, as is the case with PV. That said, many installers are also PV installers and are likely to be motivated to do the right thing on a voluntary basis. Additionally, CEC has worked with state and territory governments to promote battery endorsement, for example by making it mandatory to use a battery endorsed installer to be eligible for incentivised pilot schemes such as the ACT government's 'Next Generation Energy Storage Grants' (ACT Government 2016).

Major brands are already providing training for their electrical field staff or stipulating that the third-party contractors that they engage must have 'battery storage endorsement'. Furthermore, there is general expectation that the insurance sector will be a stronger driver on the basis that policies will be void if installers do not adhere to best safety practice.

Towards a more enduring (potentially regulatory) solution to encourage industry engagement and adherence to safety standards, a number of industry stakeholders are calling for changes to state- and territory-based electrical safety standards. In Australia, electrical safety regulatory functions are the responsibility of the state and territory governments. At the moment battery systems are not captured under state- and territory-based electrical safety rules. Such policy changes could be coordinated through the Electrical Regulatory Authorities Council (ERAC) to ensure consistency across all jurisdictions.

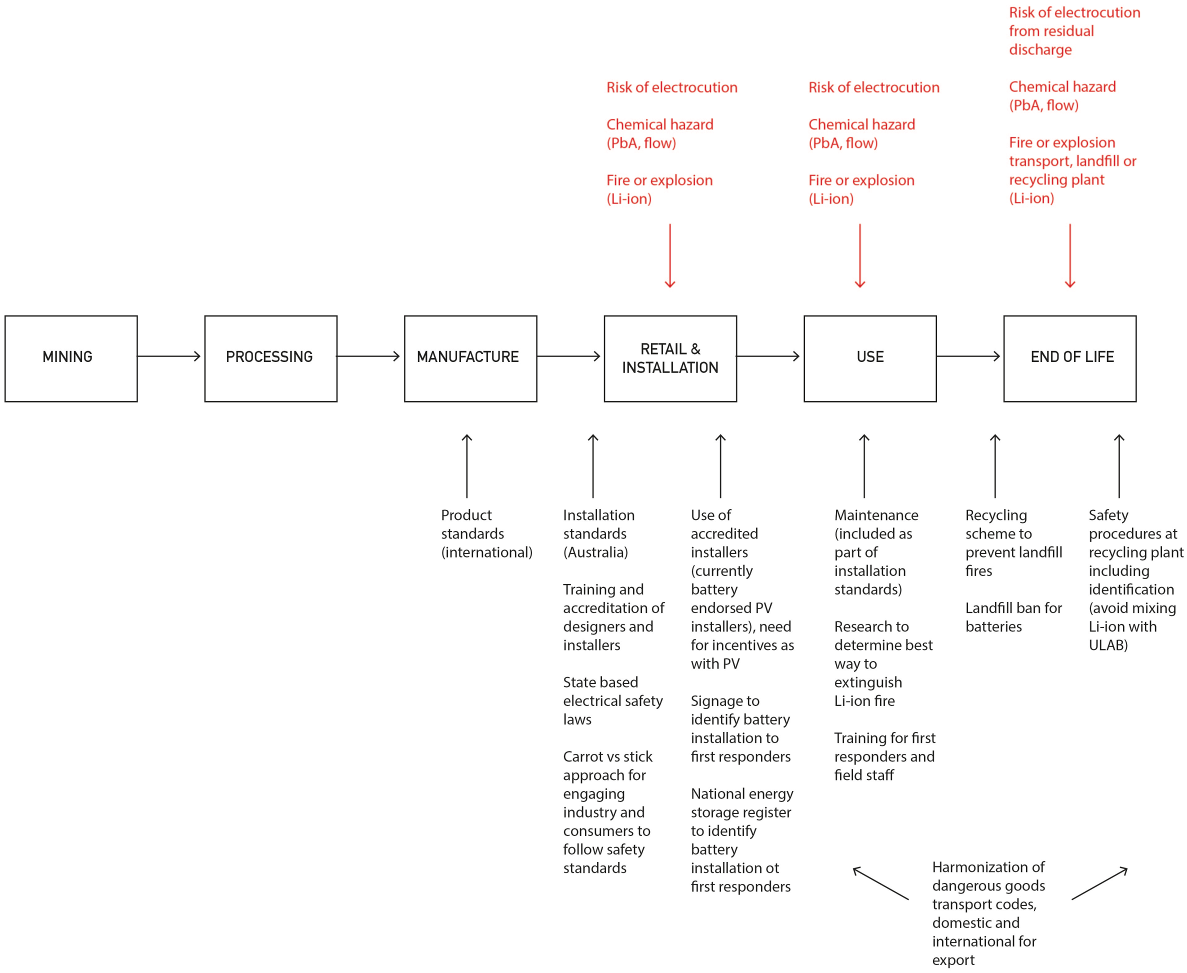

Figure 3: Impacts and key intervention points for safety across battery supply chains

8.2.2 Intervention points for end-of-life management

Encouraging investment in end-of-life management infrastructure is an important priority, however currently there is neither the economic nor policy driver to incentivise investment.

As shown in Figure 4, there are multiple points of intervention (most relevant to the Australian market) along the supply chain and this highlights the need to engage a range of stakeholders including retailers, installers and users, as well as the stakeholders responsible for processing and recycling at end-of-life.

The key policy levers identified include overarching policy frameworks promoting circular economy and product stewardship approaches (See Box 1), information and awareness campaigns and landfill bans or levies.

There are important opportunities to be seized in aligning efforts around safety with complementary efforts to improve end-of-life management. The areas in which these opportunities are to be found include:

- Installation/dis-installation represents a shared critical leverage point for ensuring safety and establishing pathways for responsible end-of-life management. Trained personnel are required to install and decommission battery systems and training could incorporate responsible end-of-life and best practice management implemented under a nationally recognised accreditation scheme.
- Making the cost of end-of-life transparent at the point of sale (as opposed to the point of disposal) is likely to lead to better end-of-life management outcomes. This also provides a strong rationale for action now rather than in ten years when the first installations reach end-of-life.
- Consistent approaches for stakeholder engagement and awareness raising. For example, e.g. signage for safety hazards could also provide information for recyclers to ensure battery types are directed towards the correct recycling pathway.

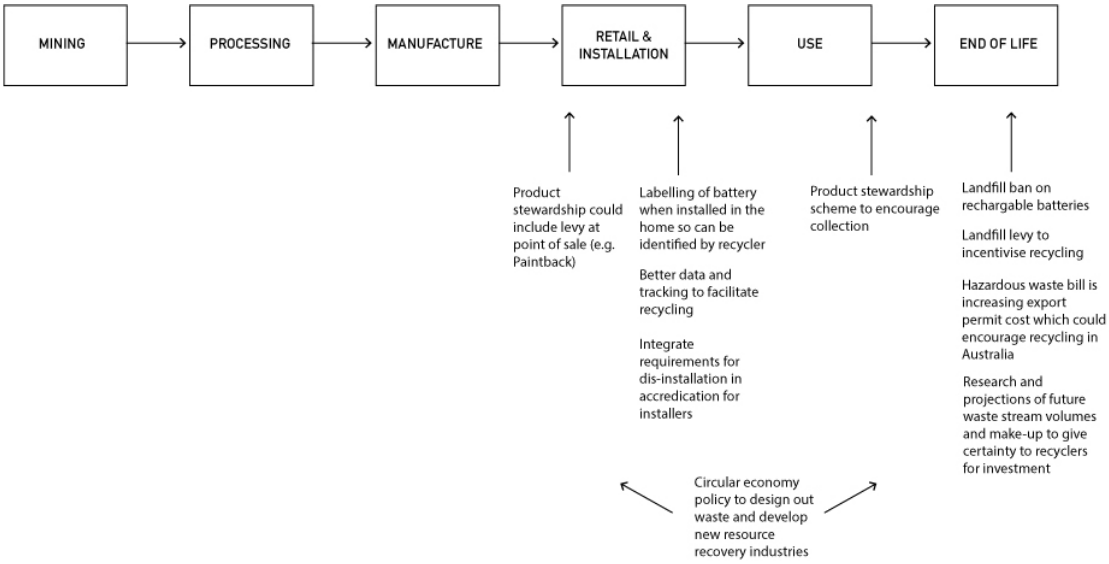

Figure 4: Key interventions for responsible end-of-life

8.2.3 Sustainable supply chains

The front end of the supply chain, particularly mining, material processing and manufacturing, has significant environmental and social impacts, which mainly fall under the categories of criticality, human rights and environmental health within our framework. As the potential interventions to address these three criteria are interrelated, we have grouped them together in a discussion on how to promote 'sustainable' supply chains. The main impacts for materials across energy storage technologies are shown in Figure 5.

Most of these impacts occur outside of Australia, which adds to the difficulty of identifying intervention points. At the same time, supply chains are extraordinarily complex. For example when addressing the impacts of cobalt mining for lithium-ion batteries, potential interventions could include mining standards and ethical sourcing requirements of processors and manufacturers. However, the supply chain has many steps; the cobalt is mined in the DRC (including by artisanal miners and locally and internationally owned companies), processed in China and Belgium, manufactured into cathodes in China and South Korea, manufactured into battery cells in Hong Kong, South Korea and Japan, and then assembled and sold as complete batteries to consumers by a number of international companies worldwide. This means for a consumer brand to be sure its components were ethically sourced it would have to undertake a complex investigation up many steps in the supply chain to influence mining practices.

Although impacts occur mainly at the front end of the supply chain, potential interventions to address these problems occur at all points. Interventions over which Australia can have influence are shown at their relevant points on the supply chain in Figure 5.

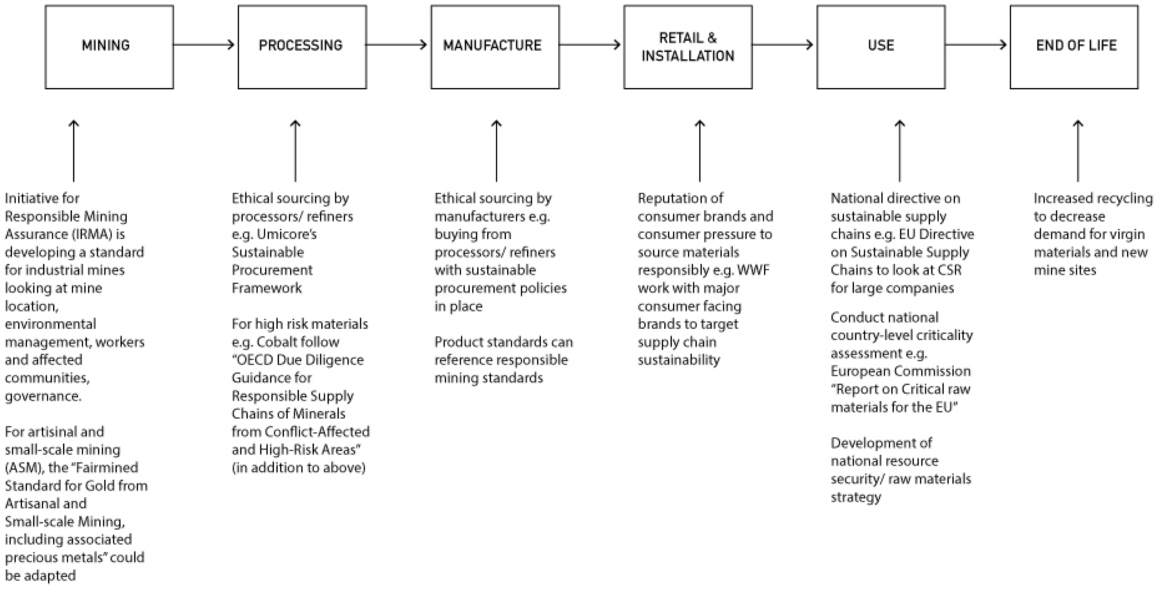

Figure 5: Key interventions for sustainable supply chains

Expert stakeholder perspectives on priority interventions

The interviews with expert stakeholders revealed that the upstream impacts of energy storage supply chains are generally not well known or understood across all the stakeholders groups, including by those working in industry, government, academia and other organisations. Only one industry and one NFP organisation had an in-depth understanding of the issues related to the sustainability and social impact of mining operations. More stakeholders were aware of potential criticality issues, but most had a limited understanding and were not able to identify any priority interventions on how to mitigate these issues. One industry stakeholder noted that securing a stable supply of lithium was high on the radar of battery manufacturing companies, but they were not aware of any social issues around lithium mining in Argentina or Chile.

One NFP organisation stakeholder commented that the most important intervention point to address the sustainability of supply chains was the reputation of major consumer brands and the expectations of corporate social responsibility.

What role can Australia play in encouraging global sustainable supply chains?

While Australia has limited touch points with the global supply chains for energy storage technologies, it also has the advantage of an advanced mining sector and a stable regulatory environment, and it is one of the earliest markets to adopt energy storage of battery technology. For this reason, Australian governments and companies can take a leading role in putting sustainable supply chains on the global agenda.

Based on the literature reviewed and feedback from stakeholders, priority interventions for Australia include:

- **Ethical sourcing and corporate social responsibility:** Companies all along the supply chain have a responsibility to ensure that they respect human rights and environmental laws. Downstream companies can influence the market by seeking transparency in their own supply chains, and looking further up the supply chains to verify the suppliers of their suppliers. Consumers can drive change in the industry by demanding that major brands act responsibly. As Australian consumers are in one of the first markets where it is expected that the number of battery installations will grow rapidly, their expectations of major brands selling in Australia will impact on international companies worldwide.
- **Support development of mining and chain-of-custody standards:** Australian governments and mining companies can support the development of mining and chain-of-custody standards. Australia has led the Steel Stewardship Forum, which has developed a chain-of-custody standard for steel and could take the lead for lithium. Product standards that may be adopted in Australia in future can be adopted so that they call upon relevant standards further up the supply chain.
- **National sustainable supply chain legislation:** The Australian government can influence the sustainability of supply chains through national legislation that requires companies to report on the environmental and social impacts of their supply chains, as many companies do voluntarily. The EU has recently introduced a directive that large public-interest entities with more than 500 employees

must disclose non-financial information in their management reports on environmental matters, employees, human rights, anticorruption and diversity (European Commission 2016). An Australian version could require companies to use existing voluntary reporting schemes such as the IS 26000 on social responsibility or the UN Global Compact.

- **Increased rates of recycling:** Australia can promote recycling and markets for second-hand materials, which will decrease the demand for raw materials. This includes the appropriate collection systems, technology and infrastructure, and financial incentives for industry and consumers to participate. Interventions to increase recycling rates are discussed in Section 8.2.3.
- **Research:** For many of the supply chain issues discussed, there is little scientific understanding of the long-term environmental, social and economic impacts to local communities and economies more broadly. There is even less consensus on the best approaches to mitigate these impacts. For example, Australian mining companies operating in Argentina could undertake research to find best practice strategies for minimising water use and for supporting sustainable economies in remote mining areas. Finding appropriate strategies to promote sustainable development in artisanal mining communities and minimise current impacts, as seen in the DRC but also in many countries worldwide, is an important question that governments, researchers and donor agencies should prioritise. As one stakeholder commented, *"no one has the answer to the artisanal mining issue"*.

Any interventions to increase the sustainability of supply chains needs to ensure they do not shift negative impacts elsewhere, or lose positive benefits in vulnerable communities. For example this has been a criticism of the Dodd-Frank Act in the U.S. This act was designed to prevent the trade in minerals that fund conflict, but has affected the livelihoods of artisanal miners.

It is important that these impacts are managed, as they pose a significant risk to the viability of the industry with flow-on effects for technology development and uptake that could hinder the transition to a low-carbon renewable energy system. This highlights the need for coordinated global initiatives to champion improved human rights and environmental impacts. These are initiatives in which Australian governments, businesses and consumers can take a leading role.

8.2.4 Energy and climate policy certainty

Lower order environmental and social impacts were identified for PHES, CAES, CSP TES and hydrogen energy. (These technologies appear in the lower quadrants in Figure 2.) As discussed in the technology chapters, this appraisal is made on the basis of: the likely deployment rates (aligned with WP1), that the exposure to any potential risk is limited to trained personnel as is typical with the large scale of deployment (i.e. utility-scale), and mature mitigation approaches owing to industrial experience.

Policy focused on environmental and safety impact mitigation is already reasonably well established for these technologies (e.g. Decourt et al. 2014; Lovegrove et al. 2012). In relation to hydrogen energy storage, for example, the core technologies (gas distribution infrastructure, combustion turbines) are relatively mature, and owing to industrial applications, there are well-established management and mitigation strategies, and handling is restricted to trained workers, limiting exposure.

For large utility-scale energy storage technologies, stakeholders interviewed for this study consistently prioritised the need for broad, consistent and certain energy and climate policy to support the uptake of renewables and incentivise infrastructure investment. The future for renewable power in Australia would seem to depend on two key uncertainties The most important of these is in ongoing energy and climate policy development, particularly the renewable energy target (RET) in the immediate term, although carbon pricing may eventually play a role. The other area of is uncertainty relates to market developments, including gas availability and price. For large-scale technology deployments, such as PHES and CSP TES that are very capital intensive, this policy uncertainty is most acute. Australia has a poor track record in major policy programs aimed at supporting large-scale low-emission energy technology deployment, e.g., the Solar Flagships Program.

For hydrogen (and battery energy storage), there is a particular need for integrated policy and planning spanning domestic energy, export energy and transport. For instance, in terms of infrastructure investment, attention needs to be given as to whether there is significant long-term investment directed towards developing battery charge stations and/or hydrogen filling stations. Whilst, transport is outside the scope of this study, this technology development pathway has broader implications for the development of safety policy because wide deployment across a range of potential end uses, and it will also require significant work to develop tailored codes, standards and regulations; substantial additional efforts would be required to harmonise the tailored policy approaches.

8.3 Summary of findings

OVERALL FINDINGS

Batteries are anticipated to have a high-rate of deployment for energy storage and there are associated adverse environmental and social impacts along the supply chain, e.g.: human rights and pollution impacts of mining; fire risk during transport, installation, use and end-of-life; and, a future waste management challenge, owing to the lack of recycling systems.

Current planning and decision-making influencing the deployment of energy storage technologies needs to acknowledge and manage these short and longer-term impacts as they pose a significant risk to the viability of the industry and could hinder the transition to a renewable energy system.

Considering the major research, development and investment in energy storage technologies, it is likely that those that will dominate the market in the coming decades are unlikely to be the same technologies that dominate the market currently. Our evaluation demonstrates the importance of assessing environmental and social impacts across the whole supply chain to mitigate potential adverse impacts ahead of the implementation of new technologies.

SPECIFIC FINDINGS

Safety risks in installation and use, emergency response, decommissioning and end-of-life

Key challenge: Current safety initiatives are happening in the right direction but at the wrong pace. Safety risks are being addressed through industry-led voluntary initiatives, including the development of installation guides, training, accreditation pathways, the establishment of a national energy storage register, as well as standards development. The level of industry and consumer awareness and engagement may be out of pace with the rapid rate of deployment and technology development.

Opportunity: There is an opportunity to promote the development of a vibrant and world-leading industry that models a culture of safety and best practice in installation and use. Fostering stakeholder awareness and incentivising the industry to engage with safety guidelines, without creating barriers for the emerging market, necessitates consistent government intervention.

Responsible end-of-life management

Key challenge: Energy storage batteries present a future waste management challenge, but if managed strategically, is a resource recovery opportunity. In the absence of an economic driver or clear policy directives there is currently no certainty for industry to invest in local end-of-life solutions for recycling and reusing storage batteries.

Opportunity: Australia has an opportunity to develop a stewardship approach to ensure the sustainable management of batteries across the whole product lifecycle. There is a strong rationale to act now to engage all stakeholders in developing a viable approach and to drive timely investment in recycling infrastructure and technology. A further impetus to act now is to coordinate with the current safety initiatives that are targeting retailers and installers–these stakeholders are critical for supporting a sustainable product stewardship scheme.

Sustainable supply chains

Key challenge: There is a paucity of data and a lack of stakeholder awareness around significant environmental and social impacts at the front-end of the supply chain, i.e. human rights and pollution impacts of mining.

Opportunity: As an early market for batteries, Australia has an opportunity to champion sustainable supply chains. Australia's expertise in mining can support international standards development and engaged consumers can demand that the major brands act responsibly that can influence brand action globally.

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