Australia's National
Science Agency

From minerals to materials

Supplementary report: Silicon

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Acknowledgements

CSIRO acknowledges the Traditional Owners of the lands that we live and work on across Australia and pays its respect to Elders past and present.

The project team would like to acknowledge the contributions of all stakeholders that provided input to this project from industry, government and academia. Appendix A of the main report 'From minerals to materials: Assessment of Australia's critical mineral mid-stream processing capabilities' includes a complete list of the organisations that provided input into to this project.

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Glossary

Abbreviations

ARENA	Australian Renewable Energy Agency
CVD	Chemical vapour deposition
EOL	End-of-life
EVA	Ethylene vinyl acetate
FBR	Fluidised bed reactor
FRELP	Full recovery end of life photovoltaic
HDRI	Hydrogen Direct Reduced Iron
IP	Intellectual property
NOx	Nitrogen oxides
OEM	Original equipment manufacturer
PERC	Passivation emitter rear contact
PV	Photovoltaic
RD&D	Research, development and demonstration
SCCO2	Supercritical CO2
Si	Silicon
SiC	Silicon carbide
SiO	Silicon monoxide
SiO2	Silicon dioxide
TCS	Trichlorosilane

Definitions

2N - 11N	Number of nines in the purity of the product. 2N corresponds to 99%, 3N to 99.9%, and 11N to 99.999999999%.
Polysilicon	High-purity silicon (6N or above) produced from metallurgical grade silicon, and which is suitable as feedstock for solar panel or semiconductor production.
Monocrystalline	Being composed of a single crystal. Usually refers to silicon blocks produced using CVD-derived silicon and the Czochralski method.
Multicrystalline	Being composed of multiple crystals fused together. Usually refers to silicon blocks produced using directional solidification.

1 Executive summary

Australia has a history of strong research in downstream solar PV activities, including the development of the passivation emitter rear contact (PERC) solar cell and solar PV recycling research. However, research, development and demonstration (RD&D) in mid-stream activities, such as the production of metallurgical silicon and polysilicon, has historically been lower in Australia, despite existing industrial production of metallurgical silicon in Western Australia.

Despite the recent oversupply of polysilicon in the global market, the global energy transition will require a 10 to 12-fold increase on current production capacity,[1] and supply chains are highly vulnerable to disruptions due to concentration.

Australia can play a role in diversifying the global silicon supply chain; however, in light of modest domestic RD&D activity in this area to date, international collaboration and RD&D efforts will be required to deliver near-term commercial outcomes and to develop the capabilities for long-term step-change innovations. This includes supporting the implementation of mature technologies in the Australian context, piloting and scaling up Australian technology, accelerating emerging technologies and growing Australian IP or establishing new capabilities in emerging technologies (Figure 1, Figure 2, and Figure 3).

This supplementary report is part of the report series *From minerals to materials: Assessment of Australia's critical mineral mid-stream processing capabilities*. The series adds to existing Australian and international literature on critical minerals and renewable energy technologies by providing a detailed picture into mid-stream processing, key areas for global risk reduction and capability development to support the energy transition in Australia.

Figure 1: Framework for assessing research, development and demonstration (RD&D) and international engagement actions.

Opportunity area	Establish new capability in emerging technologies	Accelerate emerging technologies and grow Australian IP	Pilot and scale up Australian IP	Support commercial deployment of mature technologies
RD&D actions	Build capability in emerging technology areas via fundamental and applied research projects.	Leverage Australia's strengths to progress technologies beyond the lab and grow Australian IP.	Deploy Australian IP in pilot-scale and commercial-scale demonstrations.	Support the deployment of mature technologies domestically at commercial scale, through commercial testing and validation, and cross-cutting RD&D.
International engagement actions	Engage with research institutions on capability building and knowledge sharing (e.g. joint research programs).	Partner with overseas industry, research or government on mutually beneficial sustained technology development efforts (e.g. co-funded or joint projects).	Engage with upstream offtakers to de-risk and finance pilot projects. Alternatively, demonstrate Australian technologies overseas.	Engage on commercial arrangements e.g. international technology providers, license overseas patents, attract foreign direct investment, and secure offtake agreements.

For a full description and methodology of this framework, refer to the main report *From minerals to materials: Assessment of Australia's critical mineral mid-stream processing capabilities.*

IP, intellectual property.

[1] Hallam et al. (2022) A Polysilicon Learning Curve and the Material Requirements for Broad Electrification with Photovoltaics by 2050. Solar RRL 6(10), 2200458.

Carbothermal reduction

Commercial production of metallurgical grade silicon is globally mature but faces strong pressure to decarbonise. The continued operation and expansion of this industry in Australia will require emissions reductions and RD&D infrastructure and facilities, namely industrial testing facilities for the carbothermal reduction of Australian quartz.

Australia currently produces metallurgical silicon, but despite its industrial capability, RD&D in this area is limited. Given carbothermal reduction is highly mature, collaboration with overseas equipment manufacturers will be required to deploy state of the art furnaces with low particulate emissions and energy intensity. It is also important to collaborate with research groups specialising in biocarbon (instead of coal-based) reductants for metallurgical processing to build greater domestic capability. Finally, testing the reduction of Australian quartz with various carbon reductants cannot currently be done onshore, and access to such facilities will be essential to accelerate domestic projects.

Metallothermic reduction; Electrolytic reduction; Hydrogen reduction

Emerging approaches to reducing quartz and produce metallurgical silicon, such as electrolytic, metallothermic, hydrogen or gas-based reduction, have the potential to offer cost-effective Zerocarbon neutral alternatives to carbothermal reduction. Despite their longer development timeframes and higher investment risk, these cross-cutting reduction techniques have spillover applications across other minerals and RD&D focus on this capability could support the development of other supply chains.

Partnering with international research organisations that have expertise in emerging quartz reduction techniques will be essential for knowledge sharing and capability building in Australia. Further, Australia has expertise in applying these techniques across other metals, which could be leveraged to develop domestic silicon capability. Studies are required to understand the comparative costs and lifecycle impacts of these emerging processes, and importantly, the level and type of impurities in the final product.

Chemical vapour deposition (e.g. Siemens process)

Commercial production of solar-grade silicon (polysilicon) using chemical vapor deposition techniques are commercially mature and are either highly proprietary or subject to high levels of know-how that are not easily replicated. Strong collaboration with overseas equipment providers will be required to produce polysilicon commercially in Australia.

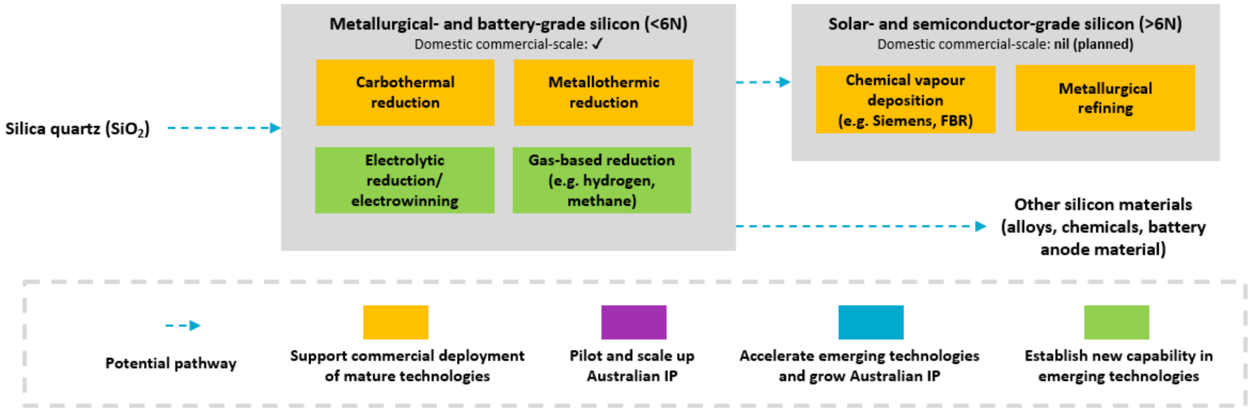
Stakeholder consultations have indicated that the viability of polysilicon production in Australia will also depend on international offtake agreements or on the integration of domestic ingot and wafer manufacturing. Enabling RD&D areas play a role in supporting the development of an integrated supply chain.

Metallurgical refining

Metallurgical refining of solar-grade silicon is mature and can be used in conjunction with, or instead of, conventional chemical vapour deposition (CVD) processes. As an alternative to CVD, this can potentially reduce barriers to entry into polysilicon production and holds potential sustainability benefits. However, lower product purities carry important market and techno-economic considerations.

Reducing the purity (and solar cell efficiency gap) with CVD-produced polysilicon, while keeping the process comparatively simple and cost-effective, can help de-risk metallurgical refining and increase its viability as a competitive option for Australia. This will require research and collaboration projects to unlock technical improvements, as well as future technoeconomic and market analyses to assess the viability of onshore production.

Figure 2: Australian RD&D opportunities across silicon mid-stream processing technologies.



Note: This diagram represents a simplified summary of research, development and demonstration (RD&D) actions and international engagement actions for Australia. However, some technologies and their variants cut across a range of maturity levels, therefore warranting multiple actions.

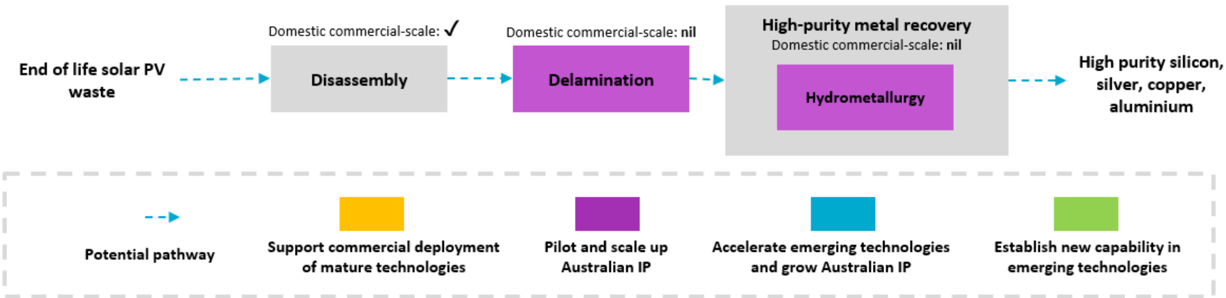
SiO_2, silica quartz; FBR, fluidised bed reactor; IP, intellectual property.

Solar PV Recycling (delamination, hydrometallurgical high purity metal recovery)

The global PV industry has been dominated by low-cost bulk and low-purity processes due to the challenging economics of PV recycling. Australia's growing PV waste stream and RD&D processes targeting greater recovery of high-quality materials could improve the viability of domestic projects. Given the global momentum in this research area and Australia's RD&D activity, there is an opportunity to pilot and demonstrate domestic IP.

RD&D focus areas include delamination technologies and hydrometallurgical recovery of high purity materials. Given many technologies have been piloted overseas, collaboration will be essential to ensure Australia's effort and investment are not duplicative.

Figure 3: Australian RD&D opportunities across solar PV recycling technologies.



Note: This diagram represents a simplified summary of research, development and demonstration (RD&D) actions and international engagement actions for Australia. However, some technologies and their variants cut across a range of maturity levels, therefore warranting multiple actions.

PV, photovoltaic; IP, intellectual property.

2 Objectives and scope

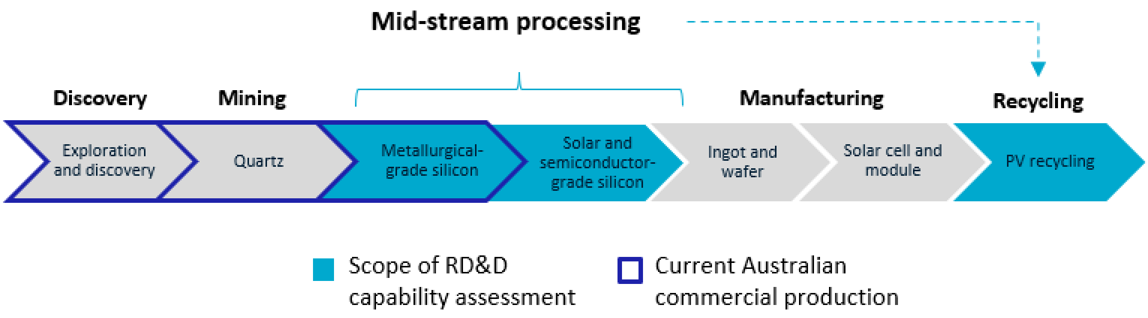
This supplementary report will focus on Australia's key silicon supply chain gaps, namely the first two steps of mid-stream value adding, as well as recovery of high value metals from solar PV waste (Figure 4).

This report aims to address several objectives:

- To communicate key current and emerging technologies underpinning the production of metallurgical and solar grade silicon, and high value recycling, with a strong focus on technologies that have been demonstrated at lab, pilot and commercial scales.
- To communicate where high levels of IP and research activity are occurring in Australia and globally, each emerging and mature technology area.
- To communicate key challenges and opportunities for Australia to build domestic IP and for collaboration with international partners.

The purpose of this analysis is to guide and inform government, industry and research sector decision-making with respect to RD&D investment and collaboration efforts across critical minerals and renewable energy technology supply chain activity.

Figure 4: Scope of silicon supplementary report and current commercial production in Australia.



PV, photovoltaic.

3 RD&D challenges and opportunities

Solar PV supply chains are well established and mature globally, underpinned by key mature extraction and refining technologies. There are, however, several emerging technologies being developed globally to enhance sustainability and cost outcomes, which are not currently commercially utilised at scale. The impetus for these innovations is largely driven by an evolving global landscape, marked by extensive decarbonisation efforts. These include a Carbon Border Adjustment Mechanism, industry net zero objectives, as well as rising social and community expectations.[2] The goals of growing global supply, achieving deeper decarbonisation and building competitive industries all serve as key drivers for emerging technologies.

This section will discuss the RD&D challenges and opportunities relating to mature and emerging technologies for producing various grades of silicon, as well as recovering silicon and other metals from solar PV waste. The technologies discussed and their levels of maturity are summarised in (Figure 5 and Figure 6).

- Section 3.1 will cover technologies used to produce metallurgical grade (2N) and battery grade (3-4N) silicon; carbothermal reduction, electrolytic reduction, metallothermic reduction and gas-based reduction. The metallurgical and battery grade silicon can then be used as a feedstock into solar and semiconductor grade silicon but can also be sold into markets such as the chemicals, alloys and battery markets. [3]
- Section 3.2 will cover solar grade (6-11N) and semiconductor grade (11N and above) silicon production, also referred to as polysilicon. It should be noted that although solar photovoltaic cells theoretically require 6N purity at minimum to enable conversion of sunlight, the current industry standard is 9-11N purity monocrystalline silicon, to support the market push towards increasingly efficient solar cells.[4]
- Section 3.3 will cover crystalline silicon solar PV recycling, with a focus on the recovery of high value, high purity materials from end-of-life PV waste, as opposed to commercially mature lower value mechanical recycling processes. This will include mechanical, thermal and chemical delamination technologies followed by the extraction and purification of high value metals and high-purity silicon.

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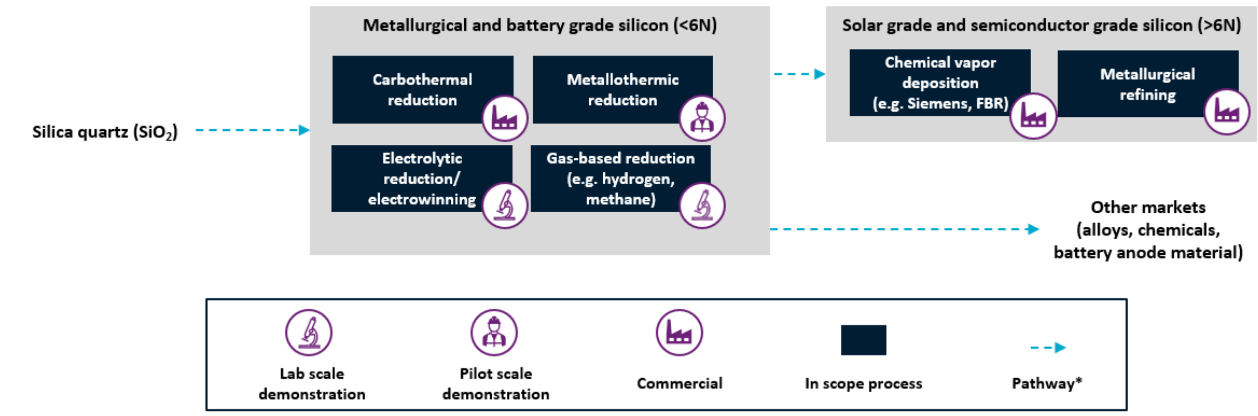
[2] European Commission (2023) Carbon Border Adjustment Mechanism. <https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en>; The World Bank (2023) Carbon Pricing Dashboard. <https://carbonpricingdashboard.worldbank.org/map_data>

[3] Purity requirements may depend on battery manufacturer specifications. HPQ Silicon (2023) HPQ Silicon: Strategic Silicon Solutions. Corporate Presentation <https://hpqsilicon.com/wp-content/uploads/2022/08/HPQ_PRESENTATION_AUG_05.pdf>

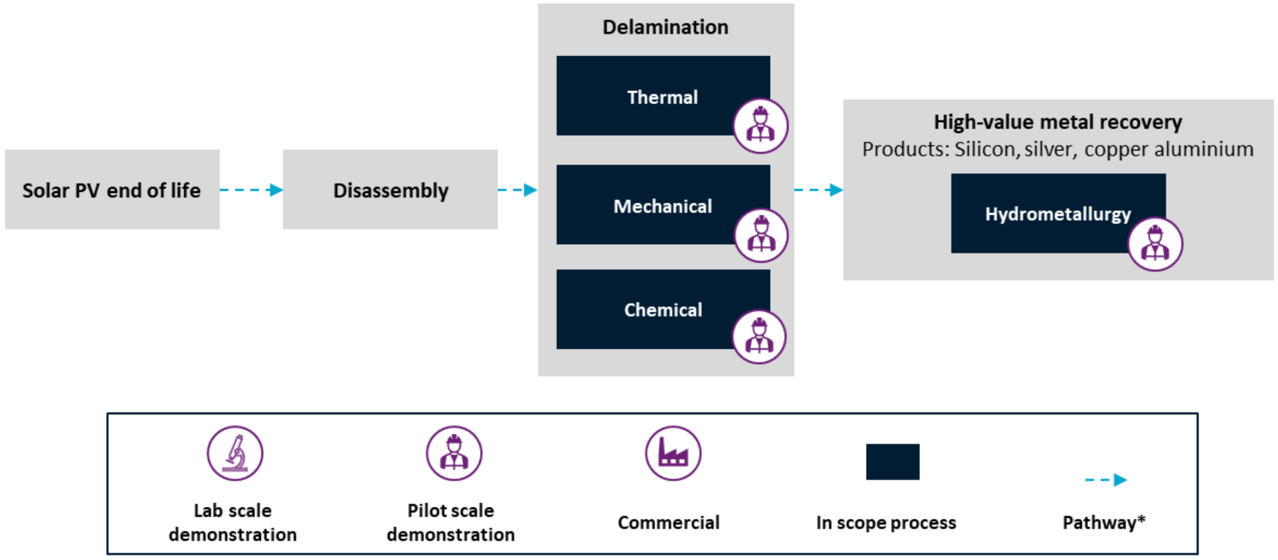
[4] Woodhouse M et al. (2018) Crystalline Silicon Photovoltaic Module Manufacturing Costs and Sustainable Pricing: 1H 2018 Benchmark and cost Reduction Road Map. NREL, US

Figure 5: Taxonomy of silicon processing technologies for the solar PV supply chain.



SiO_2, silica quartz; FBR, fluidised bed reactor.

Figure 6: Taxonomy of solar PV recycling technologies for the solar PV supply chain.

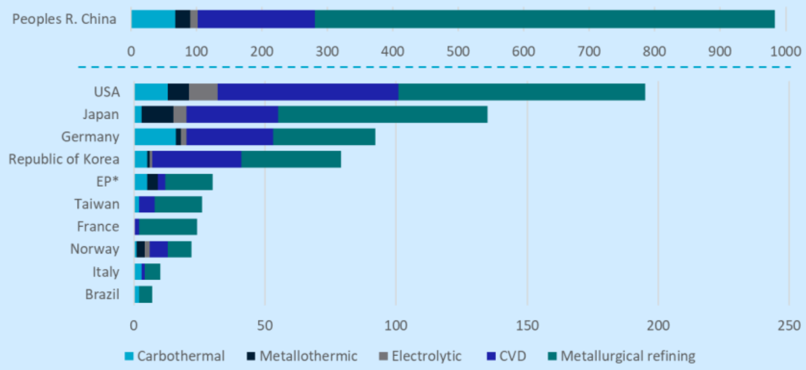


PV, photovoltaic.

Global R&D and commercialisation snapshot

Production of silicon metal and polysilicon

Figure 7: Patent output in silicon mid-stream processing technologies 2007 to 2022, by country.



*Applications filed under an entity other than a country.

Peoples R. China, Peoples Republic of China; EP, European patent application; CVD, chemical vapour deposition.

Figure 7 illustrates patent output in silicon mid-stream processing technologies by country. Overall, China accounted for 58.2% of the total patent output in the 2007-2022 interval, followed by the USA (11.5%) and Japan (8%). China led patent activity in carbothermal and metallothermic reduction technologies, whereas both China and the US led in electrolytic reduction technologies (relevant to producing metallurgical-grade and battery-grade silicon). China also led patent activity in metallurgical refining processes and in chemical vapour deposition technologies to produce solar and semiconductor grade silicon.

Figure 8: Research publication activity related to silicon throughout the 2007 – 2023 period, by country and processing technology.

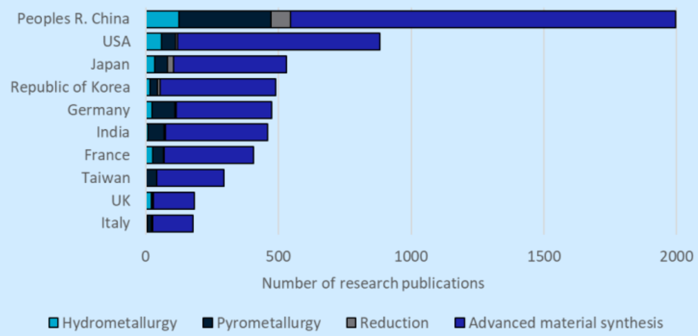
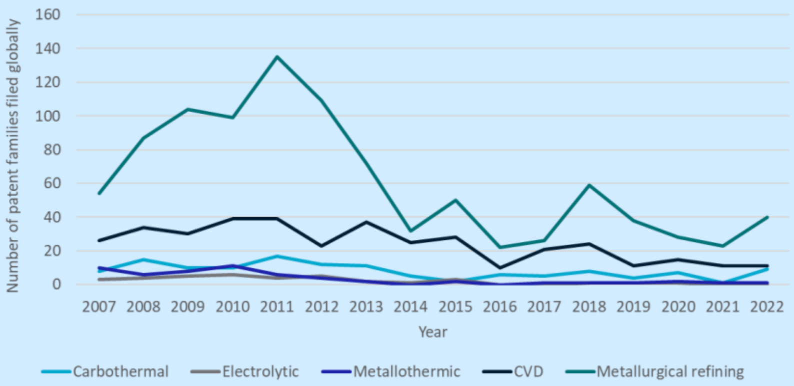


Figure 8 shows the output of research publications from 2007 to 2023 that are related to silicon, as distributed by country and processing technology. China accounts for 23% of the total, followed by the USA (10%), Japan (6%) and the Republic of Korea (5.62%).

Most publications in this analysis were related to the production of advanced materials (i.e. polysilicon and related materials) (81%). Processes associated with the production silicon metal from quartz had lower activity, with pyrometallurgical processes accounting for 5.51%, hydrometallurgical processes 10.68% and reduction processes 2.49%.

The bibliometric and patent data presented in this report is subject to limitations and has an estimated accuracy of 70% or above. For a full description of the methodology and limitations refer to the main report *From minerals to materials: Assessment of Australia's critical mineral mid-stream processing capabilities*.

Figure 9: Global patent output in silicon mid-stream processing throughout the 2007 – 2022, by year and technology.



CVD, chemical vapour deposition.

The distribution of patent families across technologies from Figure 9 shows metallurgical refining is the area of highest activity globally, accounting for 63.8% of total patents filed, followed by CVD (22.9%). All silicon mid-stream processing technologies experienced a peak in activity in the late 2000s.

Table 1: Top 10 active organisations outside of China

By publication output (all)	By patent output (all)
CNRS, **France**	Wacker Chemie, **Germany**
DOE, **USA**	Evonik Degussa, **Germany**
CEA, **France**	Shin Etsu Chemical, **Japan**
IIT, **India**	High Purity Silicon (SUMCO), **Japan**
Helmholtz Association, **Germany**	Highland Materials, **USA**
University of California, **USA**	Tokuyama, **Japan**
CNR, **Italy**	KIER, **Republic of South Korea**
Grenoble University, **France**	JNC, **Japan**
Fraunhofer Gesellschaft, **Germany**	JX Nippon Mining and Metals, **Japan**
SKKU, **Republic of Korea**	Toho Titanium, **Japan**

The bibliometric and patent data presented in this report is subject to limitations and has an estimated accuracy of 70% or above. For a full description of the methodology and limitations refer to the main report *From minerals to materials: Assessment of Australia's critical mineral mid-stream processing capabilities*.

3.1 Production of metallurgical grade and battery grade silicon metal

Silicon metal is a key feedstock for producing solar and semiconductor grade silicon that is used in solar PV and electronic products. Silicon metal of a sufficient purity can also be used in battery anodes. To produce silicon metal, silica quartz (or silicon dioxide) must be first be reduced. Commercially this is done within a furnace by using a carbon material as a reductant (see Section 3.1.1).[5] Concerns around emissions have spurred improvements in this process, as well as innovation in alternative reduction processes including metallothermic reduction, electrolytic reduction, and gas-based reduction of silica quartz.[6]

For the solar PV and semiconductor supply chains, metallurgical grade silicon is further refined to achieve solar and semiconductor grade purities. This is done via chemical vapor deposition (CVD) techniques (e.g. the Siemens process) or alternative metallurgical refining techniques (see Section 3.2.2).

3.1.1 Carbothermal reduction

Carbothermal reduction is a widely used process across several industries to reduce compounds into metals using carbon as a reductant. To produce silicon, a silica (SiO_2) source, such as quartz, is reduced in a submerged arc furnace or electric arc furnace at temperatures of approximately 2000 °C using a standard reducing mixture comprising coal or charcoal.[7] This results in metallurgical grade silicon of roughly 2N (or 99-99.8%) purity.

Carbothermal reduction is an energy intensive process and despite electrification, the use of a carbon reductant inherently generates process emissions.

TECHNOLOGY STATE OF PLAY

Carbothermal reduction is the dominant and most mature pathway for solar PV supply chains. Australia has one commercial producer of metallurgical grade silicon via carbothermal route. Simcoa mines quartz in WA and uses a submerged arc furnace to reduce the quartz into metallurgical silicon. Simcoa is looking at expanding its quartzite mining operations in the Wheatbelt region of WA.[8]

Despite being a mature technology, innovative carbothermal reduction techniques are being developed overseas to reduce energy, costs and emissions, and target higher grades of silicon (e.g. battery grade) compared to mature carbothermic reduction practices.

For example, HPQ Silicon, Canada, has developed a process to convert quartz into silicon in a vacuum furnace using a plasma arc.[9] Pilot testing in 2023 validated that the process can achieve 3N silicon, and the

[5] Chigondo F (2018). From metallurgical-grade to solar-grade silicon: an overview. Silicon, 10, 789-798.

[6] Chigondo F (2018). From metallurgical-grade to solar-grade silicon: an overview. Silicon, 10, 789-798.

[7] Ringdalen E and Tangstad M (2016) Phase transformations in quartz and its effects on furnace operations. Silicon for the Chemical and Solar Industry XIII. SNTEF and NTNU <https://www.ntnu.no/trykk/publikasjoner/Silicon%20for%20the%20chemical%20and%20solar%20industry%20XIII/HTML/files/assets/common/downloads/page0277.pdf>

[8] EPA (2022) North Kiaka Quartzite Mina. Government of WA <https://www.epa.wa.gov.au/proposals/north-kiaka-quartzite-mine>

[9] HPQ Silicon (2023) HPQ Silicon: Strategic Silicon Solutions. Corporate Presentation <https://hpqsilicon.com/wp-content/uploads/2022/08/HPQ_PRESENTATION_AUG_05.pdf>

company is also targeting 4N+ purities for the battery market.[10] The single step process removes the need for oxidative refining and additional purification typically required to reach these purities. [11]

Despite being commercially active, Australia does not have high levels of RD&D activity in carbothermal reduction of silicon. However, Australia does have carbothermal reduction research capabilities with respect to other materials.[12] The availability and transferability of this skillset to the silicon RD&D requires further investigation.

The global patent analysis found 7.7% of filings between 2007 and 2022 were related to carbothermal reduction technologies. Patent activity trends indicate that carbothermal reduction is still an area of ongoing RD&D activity, despite being a mature technology, with activity having peaked in the early 2000s. Global patent activity is dominated by China where close to 50% of patents were filed in the last 15 years.

The following table summarizes the RD&D focus areas for carbothermal reduction of quartz:

Table 2: Global RD&D focus areas for carbothermal reduction.

RD&D FOCUS AREAS	
Carbothermal reduction	• Improvements in arc furnace technology including desulphurisation (if coal reductants are used), reduction of nitrous oxide (NO_x) emissions and heat recovery.[13] • Improvements in bio-reductants such as sustainably sourced charcoal and biomass-based briquettes to replace low ash coal.[14] • Identifying alternative low-cost silica sources (e.g., sand; rice husks; diatomaceous earth), and novel carbothermal reduction processes that can process these materials (e.g. induction furnaces).[15]
Infrastructure and facilities	• Industrial testing facilities for quartz and carbon reductants, performed to an industry standard.
Supporting research domains	• Development of a quartz reserve database to increase understanding of Australian resources and their suitability for various applications. • Development of biomass supply chains.

[10] HPQ Silicon (2023) HPQ Silicon Gen3 QR Pilot Plant Produces 3N+ Silicon (99.92% Si) in a Single Step. TSX and OTCQX Announcement <https://hpqsilicon.com/wp-content/uploads/2023/06/HPQ-QRR-UPDATE-June_1_23_VER_FINAL_CL3.pdf>; HPQ Silicon (2023) HPQ Silicon: Strategic Silicon Solutions. Corporate Presentation <https://hpqsilicon.com/wp-content/uploads/2022/08/HPQ_PRESENTATION_AUG_05.pdf>

[11] HPQ Silicon (2023) HPQ Silicon Gen3 QR Pilot Plant Produces 3N+ Silicon (99.92% Si) in a Single Step. TSX and OTCQX Announcement <https://hpqsilicon.com/wp-content/uploads/2023/06/HPQ-QRR-UPDATE-June_1_23_VER_FINAL_CL3.pdf>; HPQ Silicon (2023) HPQ Silicon: Strategic Silicon Solutions. Corporate Presentation <https://hpqsilicon.com/wp-content/uploads/2022/08/HPQ_PRESENTATION_AUG_05.pdf>

[12] UNSW (2022) SMaRT's Green Steel 2.0 research explained <https://www.smart.unsw.edu.au/news-events/news/smarts-green-steel-20-research-explained>; Raj P et al (2020) Silicon carbide formation by carbothermal reduction in the Achson process: A hot model study. Thermochimica Acta <https://doi.org/10.1016/j.tca.2020.178577>

[13] Stakeholder consultations

[14] SINTEF, NTNU and NIBIO (2022) BioCarbUp: Optimising the biocarbon value chain for sustainable metallurgical industry.

[15] Nagahata R et al. (2021) Efficient carbothermal reduction of diatomaceous earth to silicon using microwave heating. Materials Chemistry and Physics, 257, 123744. <https://doi.org/10.1016/j.matchemphys.2020.123744>

3.1.2 Electrolytic reduction

Electrolytic reduction is a process used to extract or purify metals, whereby an electric current is passed between an anode and a cathode through a solution or electrolyte, resulting in the metals of interest being deposited onto the cathode. There are a few of variations on this process, namely electrowinning and electro-refining.

For silica quartz reduction, molten salt electrolysis is used (as opposed to electrolysis in a solution) due to silica quartz being more resistant to reduction processes. RD&D efforts overseas have focused on the development of electrolytic methods to produce silicon from silica quartz (SiO_2), due to its potential to lower carbon emissions compared to current carbothermal reduction processes used in industry.[16]

Electrolytic processes for silicon production can be done in various ways. One pathway is to reduce the silica quartz (SiO_2) in a molten salt or molten oxide electrolyte at high temperatures.[17] The other pathway is to first convert the silica to a silicon halide precursor (e.g. silicon tetrachloride), making it easier to reduce via electrolysis at lower temperatures. [18]

Due to its ability to reduce refractory metal oxides (more difficult to reduce), molten salt electrolysis is also an area of interest for recovery, separation and purification of other critical minerals such as rare earths, niobium, tantalum and rhenium, and can play an important role in extraction from wastes. [19] However, challenges remain when applying electrolytic reduction for silicon, namely low throughput, the high temperature requirements and energy costs, and the need for a carbon anode. [20]

TECHNOLOGY STATE OF PLAY

Electrolytic reduction technology is not currently in commercial use for silicon production, due to the several technical hurdles that are yet to be overcome.[21] However, it has been demonstrated at lab and may have been undertaken at pilot scales in China.

The grades of silicon that can be obtained from electrolytic processes is unclear. The highest purity publicly reported at lab scale has been 5N.[22] For molten salt electrolysis, a pilot scale project has recently been reported in China yielding purities of 4N silicon.[23]

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[16] Padamata et al. (2023) Silicon electrowinning by molten salts electrolysis. Frontiers in chemistry, 11, 1133990. https://doi.org/10.3389/fchem.2023.1133990; Tian et al. (2032) Recent Advances in Electrochemical-Based Silicon Production Technologies with Reduced Carbon Emission. Research. 18;6:0142. doi: 10.34133/research.0142. PMID: 37214200; PMCID: PMC10194053.

[17] Kero et al. (2022) Technologies with potential for climate neutral silicon production. Silicon for the chemical and solar industry XVI, SINTEF. <https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4121151>; Yasuda K and Nohira T (2022) Electrochemical production of silicon. High Temperature Materials and Processes. <https://doi.org/10.1515/htmp-2022-0033>

[18] Kero et al. (2022) Technologies with potential for climate neutral silicon production. Silicon for the chemical and solar industry XVI, SINTEF <https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4121151> ; Yasuda K and Nohira T (2022) Electrochemical production of silicon. High Temperature Materials and Processes. <https://doi.org/10.1515/htmp-2022-0033>

[19] Li M et al. (2023) A review on the extraction and recovery of critical metals using molten salt electrolysis. Journal of Environmental Chemical Engineering <https://www.sciencedirect.com/science/article/pii/S2213343723004852>; Xi X et al. (2020) Applications of molten salt and progress of molten salt electrolysis in secondary metal resource recovery. <https://link.springer.com/article/10.1007/s12613-020-2175-0>

[20] Kero et al. (2022) Technologies with potential for climate neutral silicon production. Silicon for the chemical and solar industry XVI, SINTEF. <https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4121151>

[21] Kero et al. (2022) Technologies with potential for climate neutral silicon production. Silicon for the chemical and solar industry XVI, SINTEF. <https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4121151>

[22] Tian F et. al. (2023) Recent advances in electrochemical-based silicon production technologies with reduced carbon emissions. Research. <doi: 10.34133/research.0142>

[23] Yu Z et al. (2019) Pilot-plant production of high-performance silicon nanowires by molten salt electrolysis of silica. Industrial & Engineering Chemistry Research <https://pubs.acs.org/doi/full/10.1021/acs.iecr.9b04430>

Australia has limited RD&D activity in this area for silicon, however Australia may be able to leverage its capabilities in molten salt electrolysis of other metals to develop further capability in the silicon space. For example, in 2016 a research program between UniSA and Centrex explored the extraction and purification of metals from silicate minerals using molten salts.[24] Further analysis would be required to assess the availability and transferability of skills to electrolytic silica reduction.

The global patent analysis found 2.1% of filings between 2007 and 2022 were related to electrolytic reduction technologies. In the early 2000s, during the solar boom,[25] IP activity in electrolytic reduction of silicon was high but this has declined over the last 10 years. IP activity for electrolytic reduction of silicon is less concentrated than other technology areas, with the majority of patent families filed in the US (31%), China (31%) and Japan (14%).

3.1.3 Metallothermic reduction

Metallothermic reduction is a process used to obtain a metal or alloy from an ore or a compound. In this process, a reactive metal is used as the reducing agent (instead of a carbon) to reduce the ore or compound to its elemental form. This process can be used to reduce silica quartz to produce elemental silicon - using metals such as aluminium or magnesium - eliminating the need for a carbon reductant and therefore minimising process emissions from the reduction step.[26] Alternatively the silica quartz can first be converted to a silicon halide (e.g., silicon tetrachloride) which is easier to reduce.[27] Metals that are being considered as reductants for the silicon halide reduction process include Aluminium (Al), Magnesium (Mg), Zinc (Zn), sodium metal (Na) or potassium metal (K).[28]

This process is being considered due to its low emissions and potentially low cost; however, challenges remain. For this process to be considered carbon neutral, the metals used in the process would have to themselves be produced at net zero emissions.[29] Additionally some of the metals used as reductants can have high embodied emissions, depending on the metal used.[30]

The grades of silicon that can be obtained from metallothermic processes are unclear, however sources indicate a range of purities could be achieved depending on the quality of the feedstock, the processes and subsequent purification steps.

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[24] UniSA (2016) Molten salt technology to benefit mining industry. <https://www.unisa.edu.au/media-centre/Releases/2016-Media-releases/Molten-salt-technology-to-benefit-mining-industry-/>; Centrex Metals (2016) Quarterly Activities Report. ASX Announcement. <https://announcements.asx.com.au/asxpdf/20160722/pdf/438qyqs83f7svh.pdf>

[25] Junfeng L et al. (2007) China Solar PV Report 2007. China Renewable Energy Association, Greenpeace China, European PV Industry Association, WWF. <https://www.understandchinaenergy.org/china-solar-pv-report-2007/>

[26] Vernon et al. (2022) Australian Silicon Action Plan. PricewaterhouseCoopers, Australia.

[27] Kero et al. (2022) Technologies with potential for climate neutral silicon production. Silicon for the chemical and solar industry XVI, SINTEF <https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4121151>

[28] Kero et al. (2022) Technologies with potential for climate neutral silicon production. Silicon for the chemical and solar industry XVI, SINTEF. <https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4121151>

[29] Kero et al. (2022) Technologies with potential for climate neutral silicon production. Silicon for the chemical and solar industry XVI, SINTEF. <https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4121151>; Alcoa (2021) ELYSIS - Start of Construction of Commercial-Scale Inert Anode Cells. <https://news.alcoa.com/media-center/alcoa-in-the-headlines/alcoa-in-the-headlines-details/2021/ELYSIS-Additional-20-million-in-federal-funding/default.aspx>

[30] Kero et al. (2022) Technologies with potential for climate neutral silicon production. Silicon for the chemical and solar industry XVI, SINTEF. <https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4121151>; Alcoa (2021) ELYSIS - Start of Construction of Commercial-Scale Inert Anode Cells. <https://news.alcoa.com/media-center/alcoa-in-the-headlines/alcoa-in-the-headlines-details/2021/ELYSIS-Additional-20-million-in-federal-funding/default.aspx>

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Metallothermic reduction technology is not currently in commercial use for silicon production. While some metallothermic reduction technologies were developed and commercialised in the past, carbothermal and Siemens became the dominant processes used across the silicon and polysilicon industry.[31]

However, there have been some recent pilot scale demonstrations of metallothermic reduction due to its potential to reduce costs and emissions compared to carbothermic reduction.

Recent examples include the EU-funded SisAl Pilot project, which aims to produce metallurgical grade silicon or solar grade silicon precursors from aluminothermic reduction of quartz. The pilot project is headed by the Norwegian University of Science and Technology (NTNU), with a consortium of 22 companies and nine research institutes.[32]

RD&D activity in metallothermic reduction for silicon production is currently low in Australia. However, Australia may be able to leverage its capability in metallothermic reduction of other metals, which exists at various research institutions and in the ferroalloy industries.[33] The availability of this skillset in Australia and its applicability to developing metallothermic silicon production requires further investigation.

The global patent analysis found 3.4% of filings between 2007 and 2022 were related to metallothermic reduction technologies. Like other areas of silicon production, IP activity in metallothermic reduction of silicon has been a declining area of patent activity since the solar boom in the early 2000s, and patent families were predominantly filed in China (roughly 40%).

3.1.4 Gas-based reduction

Hydrogen (H_2) and methane (CH_4) can be used as reducing agents for various metals and are being investigated for their potential to reduce emissions in heavy industries such as steelmaking and aluminium.

Gas-based reduction methods are also being considered to reduce silica quartz (SiO_2) to silicon metal (Si).

Because silica is a very stable compound, hydrogen reduction is challenging and requires extremely high temperatures. While still in their infancy, processes using plasma technology have shown potential to reduce silicon oxides at a lower temperatures.[34] Other gas-based pathways include the use of methane to produce silicon carbide (SiC) as an intermediate product, which could then be carbothermically reduced.[35]

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[31] Yasuda K and Okabe T (2012) Solar-grade silicon production by metallothermic reduction. Jom, 62, 94-101.

[32] SisAl Pilot (2023) SisAl Pilot. <https://www.sisal-pilot.eu/>

[33] Avarmaa K et al. (2022) Utilization of scrap metals as reductants for improved Ni and Cu recoveries in copper smelting. Journal of Sustainable Metallurgy. <https://www.researchgate.net/publication/365211133_Utilization_of_Scrap_Metals_as_Reductants_for_Improved_Ni_and_Cu_Recoveries_in_Copper_Smelting>; Swinbourne D and Arnout S (2017) Thermodynamic model of metallothermic smelting of ferromolybdenum <https://www.tandfonline.com/doi/full/10.1080/03719553.2017.1421421>; Haque N and Norgate T (2013) Estimation of greenhouse gas emissions from ferroalloy production using life cycle assessment with particular reference to Australia. Journal of Cleaner Production. <https://doi.org/10.1016/j.jclepro.2012.08.010>;

[34] Dalaker H (2021) HyPla - Hydrogen plasma for CO2-free metal production. <https://www.sintef.no/en/projects/2020/hypla-hydrogen-plasma-for-co2-free-metal-production/>

[35] Kero et al. (2022) Technologies with potential for climate neutral silicon production. Silicon for the chemical and solar industry XVI, SINTEF. <https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4121151>

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While gas-based reduction of metals is widely being researched globally (e.g., the direct reduction of iron in steelmaking), gas-based reduction of silica is in its infancy. This technology remains at lab scale internationally.

For example, SINTEF in Norway are currently conducting a lab scale project (HyPla) to develop a novel two-step silicon production process that uses hydrogen in plasma state as reductant instead of carbon.[36]

Australia has low RD&D activity in gas-based reduction of silicon; however, Australia may be able to leverage its capabilities in hydrogen reduction of other metals. For example, Calix is designing a demonstration scale Hydrogen Direct Reduced Iron (HDRI) with backing from the Australian Renewable Energy Agency (ARENA).[37]

Global IP activity for gas-based reduction processes was not included in this report due to the emergence of the technology and limited data availability.

[36] SINTEF (2023) HyPla – Hydrogen plasma for CO_2-free metal production. <https://www.sintef.no/en/projects/2020/hypla-hydrogen-plasma-for-co2-free-metal-production/>

[37] DCCEEW (2022) New iron reduction technology targets low emissions steel. <https://www.energy.gov.au/news-media/news/new-iron-reduction-technology-targets-low-emissions-steel>

The following table summarizes the key RD&D areas of focus in emerging alternatives to carbothermal reduction technology, namely electrolytic reduction, metallothermic reduction, and gas-based reduction:

Table 3: Global RD&D focus areas for electrolytic reduction, metallothermic reduction, and gas-based reduction.

RD&D FOCUS AREAS	
General	• For all emerging reduction technologies, achieving higher silicon purities to unlock new markets (including the development of cost-effective additional purification steps). • If silicon halides are used, assessing novel low emission pathways for halide production.[38] • Management of waste slags from electrolytic and metallothermic processes will also be important.[39]
Electrolytic reduction	• For electrolytic reduction, increasing yield, overcoming slow reduction rates and low current efficiency, reducing temperatures required and high energy costs, finding low-cost carbon-neutral reductants.[40]
Metallothermic reduction	• For metallothermic reduction, development of low-emission and low-cost metal reductants e.g., net zero aluminium and magnesium.[41]
Gas-based reduction	• For gas-based reduction, development of plasma processes (the use of electrically charged gases) to overcome current limitations of hydrogen reduction when applied to challenging materials like silica.[42]

3.1.5 Implications for Australia

Metallurgical silicon is the feedstock to produce highly pure polysilicon and is therefore a key step in solar PV supply chains. Moreover, it is relevant for lithium-ion batteries, which use increasing amounts of silicon as part of composite anode materials.

The IEA estimates that, under its Announced Pledges Scenario, demand for silicon will increase from 816.2 kt (thousand metric tons) in 2022 to 2,200.5 kt in 2050, driven primarily by solar PV and electric vehicles.[43] These two applications are a prominent part of the global adoption of clean energy technologies, making

[38] Kero et al. (2022) Technologies with potential for climate neutral silicon production. Silicon for the chemical and solar industry XVI, SINTEF. <https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4121151>

[39] Li M et al. (2023) A review on the extraction and recovery of critical metals using molten salt electrolysis. Journal of Environmental Chemical Engineering. <https://www.sciencedirect.com/science/article/pii/S2213343723004852>

[40] Kero et al. (2022) Technologies with potential for climate neutral silicon production. Silicon for the chemical and solar industry XVI, SINTEF. <https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4121151>.

[41] Kero et al. (2022) Technologies with potential for climate neutral silicon production. Silicon for the chemical and solar industry XVI, SINTEF. <https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4121151>; Alcoa (2021) ELYSIS - Start of Construction of Commercial-Scale Inert Anode Cells. <https://news.alcoa.com/media-center/alcoa-in-the-headlines/alcoa-in-the-headlines-details/2021/ELYSIS-Additional-20-million-in-federal-funding/default.aspx>

[42] Kero et al. (2022) Technologies with potential for climate neutral silicon production. Silicon for the chemical and solar industry XVI, SINTEF. <https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4121151>; Dalaker H (2021) HyPla - Hydrogen plasma for CO2-free metal production. <https://www.sintef.no/en/projects/2020/hypla-hydrogen-plasma-for-co2-free-metal-production/>

[43] IEA (2023) Critical Minerals Data Explorer. Announced Pledges Scenario – Silicon. <https://www.iea.org/data-and-statistics/data-tools/critical-minerals-data-explorer>.

metallurgical silicon a large market opportunity,[44] and a strategic enabler of downstream expansion into polysilicon for countries that can achieve cost-effective production at scale.

This section discusses the opportunities for domestic RD&D and international engagement in the production of metallurgical- and battery-grade silicon (summarised in Figure 10). More details on the framework used can be found in the main report *From minerals to materials: Assessment of Australia's critical mineral mid-stream processing capabilities*.

Figure 10: Opportunities for Australian RD&D and international engagement in the production of metallurgical grade and battery grade silicon.

Opportunity area	Establish new capability in emerging technologies	Accelerate emerging technologies and grow Australian IP	Pilot and scale up Australian IP	Support commercial deployment of mature technologies
Applicable Technologies	• Electrolytic reduction • Gas based reduction			• Metallothermic reduction • Carbothermal reduction
RD&D actions	Build capability in emerging technology areas via fundamental and applied research projects.	Leverage Australia's strengths to progress technologies beyond the lab and grow Australian IP.	Deploy Australian IP in pilot-scale and commercial-scale demonstrations.	Support the deployment of mature technologies domestically at commercial scale, through commercial testing and validation, and cross-cutting RD&D.
International engagement actions	Engage with research institutions on capability building and knowledge sharing (e.g. joint research programs).	Partner with overseas industry, research or government on mutually beneficial sustained technology development efforts (e.g. co-funded or joint projects).	Engage with upstream offtakers to de-risk and finance pilot projects. Alternatively, demonstrate Australian technologies overseas.	Engage on commercial arrangements e.g. international technology providers, license overseas patents, attract foreign direct investment, and secure offtake agreements.

Despite its maturity, carbothermal reduction of quartz is still an active area of R&D internationally, particularly with regards to reducing emissions intensity. Given Australia has existing commercial activity in this space, and capabilities in the reduction of other metals, there is an opportunity to become more active in RD&D for this area. This could help expand the industry, unlock other quartz deposits in Australia, and help lower the emissions intensity of carbothermic processes.

State-of-the-art arc furnace technology for reducing silica quartz (SiO_2) is available internationally. Equipment suppliers with advanced capabilities in desulphurisation (if coal is used as a reductant), NOx emissions reduction and heat recovery could enable more sustainable processing.[45] Further novel carbothermal reduction techniques could help produce silicon from lower grade SiO2 resources.[46] There is potential for Australia to collaborate with overseas original equipment manufacturers (OEM) to develop activity onshore and grow domestic capability, as well as partner with international research organisations.

With regards to carbon reductants, silicon producers globally (and the metallurgical industry generally) are seeking to reduce fossil-based carbon reductants and increase ratios of responsibly sourced bio-reductants such as renewably sourced charcoal.[47] The composition of the biomass source can impact emissions, end-to-end costs and the charcoal properties. The latter is key for achieving the desired silicon quality.[48]

[44] Bruce S et al. (2021) Critical Energy Minerals Roadmap. CSIRO.

[45] Stakeholder consultations

[46] Stakeholder consultations

[47] Simcoa (n.d.) Environmental Sustainability. <https://www.simcoa.com.au/environmental-sustainability-1>

[48] Surup G, Trubetskaya A and Tangstad M (2020) Charcoal as an Alternative Reductant in Ferroalloy Production: A Review. Processes, 8(11), 1432.

Australia holds high grade quartz deposits throughout Australia that are suitable for metallurgical grade silicon production, many of which are in proximity to potential biomass resources.[49] This is a comparative advantage with regards to producing silicon metal with renewable resources.[50] Analysis on available biomass resources across Australia has also been performed by AgriFutures, supported by ARENA.[51] Additionally, Australia has some activity with respect to producing lower-cost and lower-emission charcoal from various sources of biomass. In April 2024, Liberty Bell Bay was awarded a grant through the Powering the Regions Fund for its 'Biocarbon project', which is aimed at assessing the viability of using charcoal as a substitute for coal-derived coke in the smelting process.[52] However, further work would be required to determine suitability for silica reduction.[53] Due to the specific requirements of the metallurgical industry, international collaboration with key international partners could also be beneficial. For example, from 2019-2022 the NTNU, SINTEF and NIBIO in Norway initiated BioCarbUp, an initiative looking at optimizing bio-resources and biocarbon for specific metallurgical processes.[54]

A crucial area for development is the ability to test the reactivity of various carbon reductants with Australian quartz samples (in their gaseous SiO form), as well as the suitability of emerging bio-reductants. This requires industrial testing facilities where experimental reduction processes can take place, and where the resulting product can be tested for impurities. While Australia has strong materials testing laboratories, there currently aren't any industrial testing facilities for carbothermal reduction. Currently, Australia is required to collaborate with specialised overseas labs and facilities for comprehensive and reliable testing services (e.g. SINTEF).[55] However, as most testing facilities were developed with a focus on coal reductants, there is an opportunity to invest in domestic industrial testing infrastructure that offer comparable testing for bio-reductants. Localised facilities may expedite project investment and development timeframes, which is key to unlocking industry expansion.

Finally, RD&D in related and cross cutting areas such as the assessment and development of biomass supply chains, and integration of renewable energy and CCS into charcoal production and carbothermal reduction plants will also be important to support more sustainable industry development.[56]

Emerging alternatives to carbothermal reduction techniques have the potential to produce lower-cost, lower emission, and higher purity silicon products.[57] This means there is an opportunity for RD&D to enable step changes and move away from current commercial techniques that dominate the industry. Given these techniques are at lower maturity levels, this would require sustained RD&D efforts to deliver disruptive alternatives at commercial scale in the medium to long term.

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[49] This is different from high purity quartz deposits, essential for crucibles used in the polysilicon manufacturing process.

[50] Vernon et al. (2022) Australian Silicon Action Plan. PricewaterhouseCoopers, Australia.

[51] Toni Nugent (2021) Australian Biomass for Bioenergy Assessment 2015-2021. AgriFutures Australia. <https://arena.gov.au/assets/2021/04/australian-biomass-for-bioenergy-assessment-final-report.pdf>

[52] Department of Climate Change, Energy, the Environment and Water (2024) $330m investment in Australian heavy industry future. <https://minister.dcceew.gov.au/bowen/media-releases/330m-investment-australian-heavy-industry-future>

[53] CSIRO (n.d.) Low cost charcoal production. <https://www.csiro.au/en/work-with-us/ip-commercialisation/marketplace/low-cost-charcoal-production>

[54] SINTEF, NTNU and NIBIO (2022) BioCarbUp: Optimising the biocarbon value chain for sustainable metallurgical industry.

[55] SINTEF (2012) Silicon Production Research and SINTEF and NTNU. <https://www.sintef.no/globalassets/upload/materialer_kjemi/brosjyrer-faktaark/faktaark/silicon-prod-ref-web.pdf>

[56] Vernon et al. (2022) Australian Silicon Action Plan. PricewaterhouseCoopers, Australia. <https://arena.gov.au/assets/2021/04/australian-biomass-for-bioenergy-assessment-final-report.pdf>

[57] Li M et al. (2023) A review on the extraction and recovery of critical metals using molten salt electrolysis. Journal of Environmental Chemical Engineering. <https://www.sciencedirect.com/science/article/pii/S2213343723004852>; Bullon J (2022) New metallurgical way for the solar silicon production – The SisAl project. Eds Tangstad M, Rong H, Valderhaug A, Andresen B, Tveit H and Page I. Silicon for the chemical and solar industry XVI. Trondheim 2022.

Molten salt electrolysis has the potential to be an economical and more sustainable method for metal extraction and is particularly well suited for challenging metal oxides such as silicon. [58] Further research into reducing temperature and heat recovery required could overcome the energy-related barriers to scale up.

Metallothermic reduction of quartz also has the potential to produce metallurgical grade silicon or solar silicon precursors at lower cost and lower emissions, provided a carbon neutral reductant is used. The process also has potential to yield higher production rates than the currently mature carbothermal processes.[59] Alternatively, the production of silicon from halides using metallurgical reduction has shown potential to increase yields compared to mature processes such as the Siemens process which uses hydrogen, despite not achieving the same purities.[60]

Despite growing global momentum towards using hydrogen-based reductants in heavy industry, silicon has specific challenges compared to other metals, and maturity levels are low globally. However, his area could be unlocked by developing capabilities in applied plasma technologies – either domestically or with international collaboration.

Given Australia's limited RD&D activity in silicon applications, it will be necessary for Australia to leverage transferable capabilities across other metals and collaborate internationally to build capability. Furthermore, learnings from the silicon projects could generate innovation spillovers into other metal areas, including other critical or strategic minerals. For example, molten salt electrolysis capability can be applied across several other minerals (e.g., rare earths) to produce metals other than silicon, as well as separation of metals from waste. There is also an opportunity for Australia to build on its hydrogen capabilities (e.g., in steelmaking) to unlock reduction of more challenging materials such as silica. This could be of benefit to other priority metal industries requiring deeper levels of decarbonisation.

RD&D will be key to ensuring emerging processes have a lower emissions intensity than incumbent technologies, as carbon neutrality is a necessity for any new industrial activity in Australia. For electrolytic reduction, this can be enabled by the development of inert anodes, lower emission halogenation pathways and reducing the temperatures required.[61] Although metallothermic reduction does not generate CO_2, earlier steps in the process (the production of the metal reductant) can be emissions intensive, which will require RD&D to overcome. A key focus should be on developing carbon-neutral metal reductants, such as aluminium and magnesium, to mitigate emissions and enhance the overall viability of the process. Further, in the case of the silicon halide pathways, the halogenation process can generate emissions if carbon is used in the process.[62] Lifecycle analysis of end-to-end processes will be important to support development and inform piloting and scale-up decisions.

Several knowledge gaps remain with respect to emerging silicon reduction technologies, which could be supported by further technology development and cross-cutting studies. The purity levels achieved to date and the purity limits of these processes are not well understood. Furthermore, the market opportunities for silicon products of various purity levels are also not well understood. Emerging silicon reduction techniques have been shown to yield purities above 3N (metallurgical grade silicon), however the current industry

[58] Li M et al. (2023) A review on the extraction and recovery of critical metals using molten salt electrolysis. Journal of Environmental Chemical Engineering. <https://www.sciencedirect.com/science/article/pii/S2213343723004852>

[59] Bullon J (2022) New metallurgical way for the solar silicon production – The SisAl project. Eds Tangstad M, Rong H, Valderhaug A, Andresen B, Tveit H and Page I. Silicon for the chemical and solar industry XVI. Trondheim 2022.

[60] Yasuda K and Okabe T (2010) Solar-grade silicon production by metallothermic reduction. Journal of the Minerals, Metals and Materials Society. <https://doi.org/10.1002/ente.201300131>

[61] Kero et al. (2022) Technologies with potential for climate neutral silicon production. Silicon for the chemical and solar industry XVI, SINTEF. <https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4121151>

[62] Kero et al. (2022) Technologies with potential for climate neutral silicon production. Silicon for the chemical and solar industry XVI, SINTEF. <https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4121151>

standard for solar is monocrystalline material of 9-11N purity. Assessments into solar PV cells utilising silicon under 9N purity, market sizing of potential other silicon markets, and techno economic analysis of the processes themselves will be important to support and inform investment decisions.

3.2 Production of solar and semiconductor grade silicon

Highly purified silicon metal, otherwise known as solar- and semiconductor-grade silicon, is essential for solar PV and high-tech electronic device manufacturing, because impurities can affect the performance of these devices.

Attaining these grades involves purifying metallurgical-grade silicon feedstock, is typically achieved through CVD methods such as the Siemens process. [63] Although there was accelerated development of alternative routes in the late 1990s, the Siemens process remains the dominant method for producing silicon feedstock for solar cell manufacturing.[64] With that said, metallurgical techniques including refining, leaching and directional solidification can be used in conjunction with, or as an alternative to, CVD methods to achieve solar grade silicon.

The levels of product purity differ depending on the refining process used and given the industry trend towards higher efficiency solar cells, producers must carefully consider optimising purity levels and production costs. Notably, the accepted concentration of impurities in semiconductor-grade silicon is significantly lower than that in solar-grade silicon.[65]

3.2.1 Chemical vapour deposition

Chemical vapour deposition (CVD) is a widely used technique across several industries to produce high purity and advanced materials. This process involves passing a metal precursor in vapor form through a reactor, where the metal is deposited onto a surface, forming a thin film, powder, or crystal.

The most commonly used CVD method for producing solar grade silicon of 9-11N (also known as polysilicon) is the Siemens process, which holds a share of over 90% of the market.[66] The fluidised bed reactor process (FBR) makes up 6% of the market and is expected to grow to 20% in the next 10 years.[67] These processes are used due to their ability to deliver very high purity silicon (or polysilicon).

In both processes, metallurgical silicon is converted to trichlorosilane (TCS) or silane gas as a precursor. The precursor gas is decomposed and reacted with hydrogen in a reactor, with the high purity silicon deposited on a surface to obtain polysilicon. The Siemens process produces polysilicon in the form of a large crystal, whereas FBR obtains polysilicon in the form of granules. [68] A key difference between the processes is that Siemens is more mature and optimised, and the FBR process is continuous, and as a result can be less energy intensive.[69]

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[63] Chigondo F (2018) From metallurgical-grade to solar-grade silicon: an overview. Silicon, 10, 789-798.

[64] Safarian J, Tranell G, Tangstad M (2012) Processes for upgrading metallurgical grade silicon to solar grade silicon. Energy Procedia 20, 88-97.

[65] Safarian J, Tranell G, Tangstad M (2012) Processes for upgrading metallurgical grade silicon to solar grade silicon. Energy Procedia 20, 88-97.

[66] VDMA (2023) International Technology Roadmap for Photovoltaic (ITRPV) 2022 Results. 14th Edition, April 2023.

[67] VDMA (2023) International Technology Roadmap for Photovoltaic (ITRPV) 2022 Results. 14th Edition, April 2023.

[68] Ramos et al. (2015) Deposition reactors for solar grade silicon: A comparative thermal analysis of a Siemens reactor and a fluidized bed reactor. Journal of Crystal Growth, 431, 1-9. Ydstie EB (2011) Producing Poly-Silicon from Silane in a Fluidized Bed Reactor. Eds Kosyachenko L, Solar Cells: Silicon Wafer-Based Technologies. DOI: 10.5772/23723; Dazhou, Y (2018) Siemens Process. In: Yang, D. (eds) Handbook of Photovoltaic Silicon. Springer, Berlin, Heidelberg. <https://doi.org/10.1007/978-3-662-52735-1_4-1>

[69] Ramos et al. (2015) Deposition reactors for solar grade silicon: A comparative thermal analysis of a Siemens reactor and a fluidized bed reactor. Journal of Crystal Growth, 431, 1-9.

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CVD techniques are well-established globally for producing solar grade and semiconductor grade silicon of purities 9N and above. However, innovation in this area is still ongoing globally. For example, NexWafe, a German based company, has demonstrated the EpiWafer process at lab scale. The method that grows a monocrystalline silicon wafer directly from a precursor feedstock gas (either silicon tetrachloride or trichlorosilane) by depositing it onto a seed wafer. The new wafer is later detached by thermal and chemical methods.[70] Importantly, this removes the need for monocrystalline ingot pulling and wafer slicing steps in the supply chain, creating operational and environmental efficiencies.[71]

While not within the scope of this report, ingot and wafer production is the most concentrated part of the silicon supply chain and has been a key challenge for proponents seeking to localise polysilicon production and build an integrated domestic supply chain. The production of ultra-high purity quartz crucibles (a key component in ingot production) is a particularly challenging and opaque area.

Australia does not currently have any polysilicon production established onshore, nor is there significant RD&D activity in this area domestically. A study by the APVI, released in February 2024, found that a domestic manufacturing capability of 10 GW of polysilicon could be feasible deployed with investment and policy support.[72] The Australian Government allocated up to $1 billion for the Solar Sunshot program, aimed at developing domestic solar PV manufacturing capabilities across the entire PV supply chain, from polysilicon production to module assembly.[73] Furthermore, in March 2024 the Queensland Government announced support of Quinbrook's ‘Project Green Poly’, which plans to manufacture polysilicon and wafers for solar and battery technologies.[74]

Australia does have capability in CVD techniques particularly in the field of advanced materials, which could lend itself to applied capability in the silicon space.[75] Further analysis would be required to assess the availability and transferability of this skillset to the polysilicon space.

Chemical vapor deposition of silicon was the second most active area in the analysis, representing 22.9% of patent families filed in the last 15 years. Whilst 55% of these patent families were filed in China, there was also significant activity in the US (13%), Japan (9%), Germany (8%) and Korea (5%). While CVD patents experienced their peak during the solar boom in the 2000s, patents activity is ongoing in this area. This indicates that the technology is well established and is likely being continually improved.

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[70] Exawatt and Nexwafe (2022) The EpiWafer process: enabling higher efficiencies, lower costs and lower carbon emissions in PV manufacturing. <https://www.nexwafe.com/whitepaper>

[71] Exawatt and Nexwafe (2022) The EpiWafer process: enabling higher efficiencies, lower costs and lower carbon emissions in PV manufacturing. <https://www.nexwafe.com/whitepaper>

[72] ARENA (2023) APVI Silicon to Solar Study. <https://arena.gov.au/projects/apvi-silicon-to-solar-study/>

[73] ARENA (2024) Solar Sunshot. <https://arena.gov.au/funding/solar-sunshot/>

[74] Queensland Government (2024) Miles Government prioritises projects in Townsville - Mount Isa corridor. <https://statements.qld.gov.au/statements/99961>

[75] ANU (2023) Chemical vapor deposition (CVD) of 2-dimensional organic-inorganic perovskite semiconductors. <https://eng.anu.edu.au/study/projects/cvd-of-2d-organic-inorganic-perovskite-semiconductors/>; CSIRO (2023) Thin film coating technologies. <https://www.csiro.au/en/research/production/materials/thin-film-coating-technologies>

The following table summarizes the key RD&D areas of focus in CVD technology for polysilicon production:

Table 4: Global RD&D focus areas for chemical vapour deposition technology for polysilicon production.

RD&D FOCUS AREAS	
Chemical vapour deposition (CVD)	• Reactor design and optimisation of Siemens and FBR, including reducing cost and improving energy efficiency.[76] • Chemicals management, including enhancing safety as well as increasing byproduct recovery for closed loop processing or for sale into other industrial markets.[77] • Development of innovative CVD processes that could eliminate subsequent steps in the supply chain such as the ingot pulling and wafer cutting.[78]

3.2.2 Metallurgical refining processes

Metallurgical techniques can also be used to produce solar grade silicon. This involves a combination of refining, leaching and directional solidification.[79] These techniques can be implemented at different stages of the overall production process: to refine metallurgical silicon prior to undergoing CVD processes; to remove impurities after the CVD process; or as an alternative to CVD altogether. Their purpose is to remove major impurities like iron, calcium, aluminium, and titanium. Refining and leaching also facilitate the removal of boron and phosphorus, which cannot be performed efficiently by the final directional solidification step.[80]

Metallurgical refining processes utilise reactive processes (e.g. using a reactive gas, slag, or alloying element) or high temperatures and pressure (e.g. melting or evaporating) to separate or remove impurities from the silicon.[81] Directional solidification is used as the final purification step in most processes.[82] This

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[76] Zhang S et al. (2022) Study on deposition conditions in coupled polysilicon CVD furnaces by simulations. Crystals. https://doi.org/10.3390/cryst12081129; Ramirex-Marquez C et al (2018) Process design and intensification for the production of solar grade silicon. <https://www.sciencedirect.com/science/article/pii/S0959652617321248>

[77] Ramirex-Marquez C et al (2018) Process design and intensification for the production of solar grade silicon. <https://www.sciencedirect.com/science/article/pii/S0959652617321248>; Jiang L et al (2017) Fluidised bed process with silane. In Yang D (eds) Handbook of Photovoltaic Silicon. Springer, Berlin. <https://doi.org/10.1007/978-3-662-52735-1_5-1>; Priya SA et al. (2015) Design and process control of siemens polysilicon CVD reactor. 2015 Conference on power, control, communication and computational technologies for sustainable growth. Institute of Electrical and Electronics Engineers (IEEE).

[78] Exawatt and Nexwafe (2022) The EpiWafer process: enabling higher efficiencies, lower costs and lower carbon emissions in PV manufacturing. <https://www.nexwafe.com/whitepaper>

[79] Hoseinpur A et al. (2020) Kinetic study of vacuum evaporation of elements from ternary melts: case of dilute solution of P in Si-Al melts. Separation and Purification Technology 235:116284; Basnet R (2020) High Efficiency solar cells based on Czochralski-grown upgraded metallurgical-grade silicon wafers. Australian National University.

[80] Safarian J, Tangstad M (2012) Vacuum Refining of Molten Silicon. Metallurgical and Materials Transactions B 43(6), 1427–1445.

[81] Hoseinpur A, Safarian J (2021) Vacuum refining of silicon at ultra-high temperatures. Vacuum 184:109924; Sortland ØS, Tangstad M (2014) Boron Removal from Silicon Melts by H2O/H2 Gas Blowing: Mass Transfer in Gas and Melt. Metallurgical and Materials Transactions E 1(3), 211–225; Li Y, Zhang L (2021) Application of Si-Based Solvents to the Purification of Metallurgical Grade-Silicon. Separation & Purification Reviews 50(2), 115–138; Zhang Zet al. (2022) Recovery and purification of metallurgical silicon from waste silicon slag by blowing refining. Journal of Cleaner Production 371:133655.

[82] Technologies identified through literature review and the patent scan include vacuum refining; slag treatment or smelting silicon with an alloy; gas injection (e.g., argon) and high temperature plasma; application of electric currents; electron beam purification; and directional solidification.

method is used to grow an ingot while also distributing residual impurities to one side of the ingot which can then be removed. [83]

Panels manufactured with solar grade silicon from metallurgical routes have been estimated to carry a lower environmental footprint than panels made with CVD-derived polysilicon, however, this can vary from process to process.[84] However, metallurgical refining routes that bypass the CVD (or Siemens) currently result in a lower purity of silicon as compared to that obtained through CVD. As discussed earlier in the chapter, 6N purity is sufficient for solar applications but the current industry standard is much higher. The impurities that remain result in a lower efficiency solar cell.[85]

Moreover, metallurgical refining processes (not using CVD) produces multi-crystalline solar cells,[86] which have steadily ceded its market share to mono-crystalline cells over the last decade.[87] Mono-crystalline cells use polysilicon produced via a CVD process and require a different process for ingot manufacture (e.g., the Czochralski process).[88]

TECHNOLOGY STATE OF PLAY

Metallurgical refining processes in general are mature internationally and used commercially. However, the use of metallurgical refining to produce solar grade silicon (bypassing CVD methods) is commercialised but not used for large scale production due to market conditions.[89] Companies with capability in this area include REC Solar (Norway) which uses the Elkem process to refine metallurgical grade feedstock to solar grades. Their process is one of multiple possible metallurgical pathways, comprising a sequence of slag refining, acid leaching and directional solidification.[90]

Metallurgical refining process had the highest level of patent activity in this analysis, however most metallurgical refining is done in conjunction with other refining methods, and patents for this technology also included other technologies covered in this report.

[83] Forniés et al. (2019) Mass Production Test of Solar Cells and Modules Made of 100% UMG Silicon. 20.76% Record Efficiency. Energies 12(8):1495.

[84] Méndez L et al. (2021) Upgraded metallurgical grade silicon and polysilicon for solar electricity production: A comparative life cycle assessment. Science of The Total Environment 789:147969.

[85] Forniés E et al. (2021) UMG silicon for solar PV: From defects detection to PV module degradation. Solar Energy 220, 354–362.

[86] Méndez L et al. (2021) Upgraded metallurgical grade silicon and polysilicon for solar electricity production: A comparative life cycle assessment. Science of The Total Environment 789:147969.

[87] Fraunhofer Institute for Solar Energy Systems (2023) PHOTOVOLTAICS REPORT. Fraunhofer ISE, Freiburg. <https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf>

[88] Basore P, Feldman D (2022) Solar Photovoltaics: Supply Chain Deep Dive Assessment. U.S. Department of Energy. Washington D.C. <https://www.energy.gov/sites/default/files/2022-02/Solar%20Energy%20Supply%20Chain%20Report%20-%20Final.pdf>

[89] Stakeholder consultations

[90] Safarian J et al. (2012) Processes for Upgrading Metallurgical Grade Silicon to Solar Grade Silicon. Energy Procedia 20, 88–97; Zhu M et al. (2020) Phosphorus separation from metallurgical-grade silicon by magnesium alloying and acid leaching. Separation and Purification Technology 240:116614; Zhu M (2021) Silicon purification by acid leaching and slag refining techniques. Norwegian University of Science and Technology, Trondheim. <https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2738488>

The following table summarizes the key RD&D areas of focus in directional solidification for solar grade silicon production:

Table 5: Global RD&D focus areas for directional solidification technology for solar grade silicon production.

RD&D FOCUS AREAS	
Metallurgical refining	• Optimisation of the refining and leaching steps of the metallurgical pathway to minimise impurity levels (particularly phosphorus and boron) prior to directional solidification and help reduce the efficiency gap with CVD polysilicon. • Minimise the loss of silicon to solid wastes during refining processes (e.g., as part of slag refining) and develop pathways for its recovery from slag.[91] • Address efficiency-limiting factors that make multi-crystalline silicon less competitive at the cell level than monocrystalline alternatives. This includes the lower diamond-saw throughput and increased degradation effects with multi-crystalline materials.[92]

3.2.3 Implications for Australia

Polysilicon is the direct input into ingot and wafer production, integrating the downstream mining and refining with advanced manufacturing for the solar PV and semiconductor industries. Polysilicon production is highly globally concentrated and is key objective for countries seeking to participate global supply chain diversification or aiming to develop a comprehensive domestic supply chain.

Polysilicon production is also a significant market opportunity. The IEA estimates that global polysilicon production and downstream manufacturing would have to more than double by 2030, to support Net Zero Emissions by 2050.[93]

This section discusses the opportunities for domestic RD&D and international engagement in the production of solar and semiconductor grade silicon (summarised in Figure 11). More details on the framework used can be found in the main report *From minerals to materials: Assessment of Australia's critical mineral mid-stream processing capabilities*.

[91] Zhang Z et al. (2022) Recovery and purification of metallurgical silicon from waste silicon slag by blowing refining. Journal of Cleaner Production 371:133655.

[92] Forniés et al. (2019) Mass Production Test of Solar Cells and Modules Made of 100% UMG Silicon. 20.76% Record Efficiency. Energies 12(8):1495.

[93] IEA (2022) Solar PV Global Supply Chains. Executive summary. <https://www.iea.org/reports/solar-pv-global-supply-chains/executive-summary>.

Figure 11: Opportunities for Australian RD&D and international engagement in the production of solar and semiconductor grade silicon.

Opportunity area	Establish new capability in emerging technologies	Accelerate emerging technologies and grow Australian IP	Pilot and scale up Australian IP	Support commercial deployment of mature technologies
Applicable Technologies				• Metallurgical refining • Chemical vapour deposition
RD&D actions	Build capability in emerging technology areas via fundamental and applied research projects.	Leverage Australia's strengths to progress technologies beyond the lab and grow Australian IP.	Deploy Australian IP in pilot-scale and commercial-scale demonstrations.	Support the deployment of mature technologies domestically at commercial scale, through commercial testing and validation, and cross-cutting RD&D.
International engagement actions	Engage with research institutions on capability building and knowledge sharing (e.g. joint research programs).	Partner with overseas industry, research or government on mutually beneficial sustained technology development efforts (e.g. co-funded or joint projects).	Engage with upstream offtakers to de-risk and finance pilot projects. Alternatively, demonstrate Australian technologies overseas.	Engage on commercial arrangements e.g. international technology providers, license overseas patents, attract foreign direct investment, and secure offtake agreements.

To enable domestic production of polysilicon, there are several challenges that will need to be overcome. Firstly, chemical vapor deposition methods (Siemens and FBR) are well established but have significant barriers to entry including intellectual property rights (in the case of FBR) and the need for strong capability and knowhow (in the case of Siemens).[94] Polysilicon production is also subject to strong cost-competition, driven by sensitivity to energy costs in production, labour costs and capital costs.[95]

For Australia, using CVD for polysilicon production would entail integrating low-cost renewable energy, and partnering with international technology partners with strong capabilities and identifying state-of-the-art technology solutions that can minimise capital and labour requirements.[96] It would also require research into reducing commercial and policy barriers to onshore production. Moreover, the chemical precursors and hydrogen used in CVD can be dangerous if not managed appropriately.[97] Enabling onshore production will require strong collaboration to ensure that production plants meet Australia's environmental and safety standards, and to develop a workforce with appropriate skills for operation.

Metallurgical refining processes could provide an alternative for onshore production with potentially lower barriers to entry. The pathways used are mature, rely on conventional metallurgical techniques, and can be used to produce solar grade silicon. However, the lower comparative purity and the multi-crystalline nature of the silicon produced ultimately affects the efficiency of solar panels, which is lower than in monocrystalline counterparts produced with CVD-derived polysilicon.

Producing feedstock for panels with lower efficiency may be viable but will carry market and technoeconomic implications that must be considered in the Australian and global contexts. Reducing the purity and efficiency gap with CVD-produced polysilicon, while maintaining the process comparatively simple and cost-effective, can help de-risk metallurgical refining and increase its viability as a competitive

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

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

[96] Bruce S et al. (2021) Critical Energy Minerals Roadmap. CSIRO, Australia.

[97] Ramírez-Márquez et al. (2020) Inherent occupational health hazards in the production of solar grade silicon. Process Safety and Environmental Protection, 142, 285-294; Maldonado S. (2020). The importance of new "sand-to-silicon" processes for the rapid future increase of photovoltaics. ACS Energy Letters, 5(11), 3628-3632.

option for Australia. This will require research and collaboration projects to unlock technical improvements, as well as future technoeconomic and market analyses to assess the viability of onshore production.

Importantly, onshore polysilicon production from either technology necessitates offtake from an ingot and wafer manufacturer to warrant investment. Development of integrated upstream activity such as ingot and wafer production and the manufacturing of low-cost and high efficiency solar cells is a key enabler.[98] Alternatively there would need to be certainty from an overseas off-taker to incentivise polysilicon development as an export. An alternative to this would be to develop CVD processes to directly grow silicon wafers, eliminating the need for the ingot and wafer cutting steps. This can also be developed and piloted in collaboration with international proponents. However, it should be noted that development timeframes could be longer for emerging processes.

3.3 Solar PV recycling

The recycling portion of this report is focused on the dominant panel type in Australia, crystalline silicon photovoltaic (PV) panels, as opposed to thin film technologies. Commercial PV recycling today uses mechanical processes such as dismantling, crushing and separation to recover bulk materials (such as aluminium frames) and low-grade silicon. The end products obtained from these processes are typically low- to medium-quality and are not always usable in secondary markets.

In Australia, there are several solar panel recycling services available; however, their current commercial capability is limited to recycling and reclaiming the aluminium frame and junction box. Over 80% of a solar panel's materials are not recycled in Australia. This includes glass, silicon and the polymer back sheeting.[99] Significant progress in high-quality material recovery is needed to enhance resource circularity. RD&D can help drive cost reductions and improve sustainability to make the PV recycling industry viable.

This section will focus on state-of-the art recycling efforts tackling the challenging aspects of high value material recovery from solar PV waste, delamination processes, and extraction of high purity silicon and metals from solar cells. This report does not cover module dismantling (i.e., removing the aluminium frame, junction-boxes and embedded cables from the solar panels), nor low-value recycling or downcycling.

[98] Bruce S et al. (2021) Critical Energy Minerals Roadmap. CSIRO, Australia.

[99] Sustainability Victoria (2022) National approach to manage solar panel, inverter and battery lifecycles. <https://www.sustainability.vic.gov.au/recycling-and-reducing-waste/product-stewardship/national-approach-to-manage-solar-panel-inverter-and-battery-lifecycles>

Global R&D and commercialisation snapshot

Solar PV recycling

Figure 12: Patent output in silicon solar PV recycling technologies 2007 to 2022, by country.

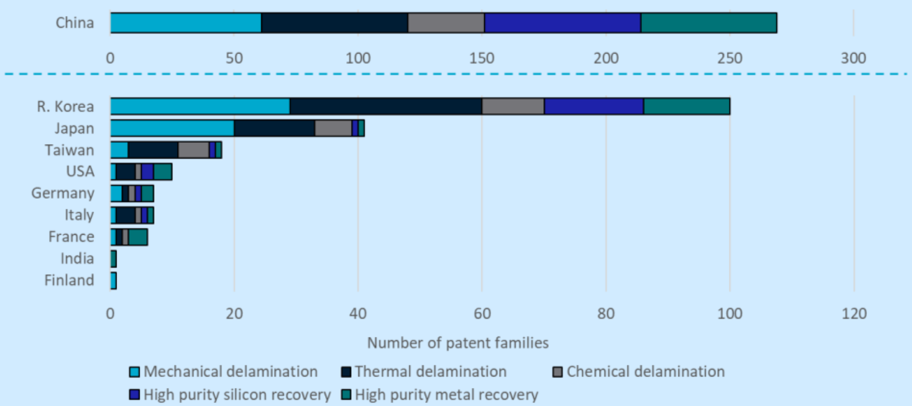


Figure 13: Research publication activity related to solar PV recycling throughout the 2007-2003 period, by country

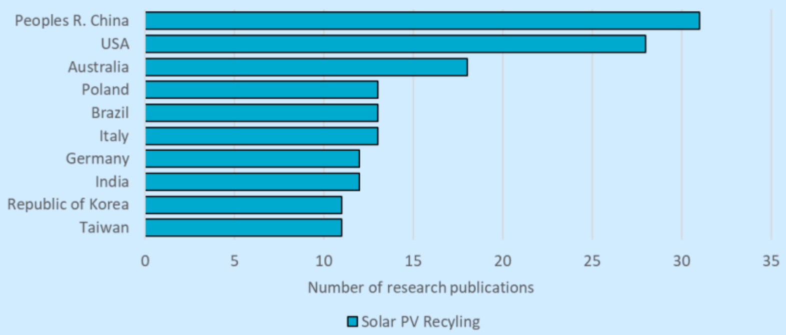
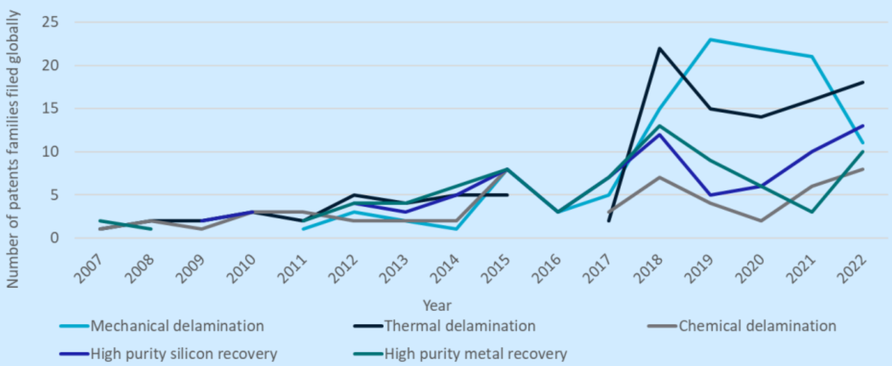


Figure 12 illustrates patent output in solar PV recycling by country. In the 2007 – 2022 interval, China led patent activity on solar PV recycling, accounting for 58.4% of total patent families across all processes analysed. South Korea, with 21.7%, and Japan, with 8.9%, complete the top 3 of countries with the highest activity.

Figure 13 illustrates research publication output by country. In the 2007 – 2023 interval, China published 32% of publications related to solar PV recycling followed by the US (28%) and Australia (18%).

The bibliometric and patent data presented in this report is subject to limitations and has an estimated accuracy of 70% or above. For a full description of the methodology and limitations refer to the main report *From minerals to materials: Assessment of Australia's critical mineral mid-stream processing capabilities*.

Figure 14: Global patent output in solar PV recycling throughout the 2007 – 2022, by year and technology.



The distribution of patent families across technologies from Figure 14 shows thermal and mechanical delamination (26% each) as the areas of highest activity globally. These are followed by technologies to recover high purity silicon (18.4%) and other metals (17.5%). Moreover, most technologies show an uptick of activity after 2017.

Figure 15: Top 10 active organisations outside of China

By research publication output	By patent output
University of New South Wales, **Australia**	KIER, **Republic of South Korea**
Fahrenheit Universities, **Poland**	Korea Electric Power, **Republic of South Korea**
UFRGS, **Brazil**	Wonkwang S&T and Wonkwang Electric, **Republic of South Korea**
DOE, **United States**	NPC, **Japan**
ENEA, **Italy**	Daewon GSI, **Republic of South Korea**
NREL, **United States**	Eco Recycling, **Italy**
University of Padua, **Italy**	Il Sung Technology, **Republic of South Korea**
AcSIR, **India**	Korea Electronics Technology Institute, **Republic of South Korea**
Colorado School of Mines, **United States**	Arizona State University, **United States**
Grenoble University, **France**	CEA, **France**

The bibliometric and patent data presented in this report is subject to limitations and has an estimated accuracy of 70% or above. For a full description of the methodology and limitations refer to the main report *From minerals to materials: Assessment of Australia's critical mineral mid-stream processing capabilities*.

3.3.1 Delamination

Crystalline silicon solar PV panels have a layered structure, where the solar cell is encapsulated in a polymer film (e.g., ethylene vinyl acetate – EVA), which acts as an adhesive for the front and back layers. The front layer is glass, while the back layer is made of various polymers. This structure is important for the longevity of the solar panel, protecting it against moisture and other types of damage. However, it is very difficult to separate at end of life.

Physical, thermal and chemical methods have been investigated to achieve more precise separation of solar panel layers. Typically, two processes (e.g., mechanical shredding followed by a chemical treatment) are used to ensure the complete removal of polymer contaminants and glass from the solar cell. The effectiveness and cost of high-purity metal recovery (explored in Section 3.3.2) depends on effective delamination. While efforts to design solar panels for circularity are under way, these are not yet commercial.

Mechanical delamination

Mechanical delamination via crushing is a mature method in the PV recycling industry, however different variations of mechanical techniques can be used. One pathway is fragmenting via mechanical crushing or various contactless methods to break the bonds between layers of materials such as glass, metals, and plastics. The mixed material can then be sorted, processed and the components recycled individually. This approach is rarely able to completely remove the polymer material from the solar cell and often requires a second thermal or chemical step. Another pathway is the removal of individual layers of materials from the cell. An example of this is the “hot knife” delamination method, whereby a heated blade slices the glass from the module.[100]

Thermal delamination

Thermal delamination involves subjecting PV modules to high temperatures to degrade or combust the polymer layers of the cell. Various methods have been explored including combustion, pyrolysis, or heating via radiation.[101] Some thermal treatments also involve the use of cryogenics, using very low temperatures to achieve delamination.

Chemical delamination

Chemical delamination processes use organic or inorganic chemicals to decompose the encapsulant layer of the solar cell.[102] The chemical treatments weaken and dissolve the adhesive bonds between the layers of the solar panel.

[100] Deng et al. (2022) Recent progress in silicon photovoltaic module recycling processes. Resources, Conservation and Recycling. <https://www.sciencedirect.com/science/article/pii/S0921344922004463>; Chouwdhury (2020) An overview of solar photovoltaic panels’ end-of-life material recycling. Energy Strategy Reviews. <https://www.sciencedirect.com/science/article/pii/S2211467X19301245>; Monteiro Lunardi et al. (2018) A Review of Recycling Processes for Photovoltaic Modules. <https://www.intechopen.com/chapters/59381>

[101] Dobra T et al. (2022) Thermal delamination of end-of-life crystalline silicon photovoltaic modules. Waste Management & Research. 40(1), 96-103. doi:10.1177/0734242X211038184.

[102] Deng et al. (2022) Recent progress in silicon photovoltaic module recycling processes. Resources, Conservation and Recycling. <https://www.sciencedirect.com/science/article/pii/S0921344922004463>; Chouwdhury (2020) An overview of solar photovoltaic panels’ end-of-life material recycling. Energy Strategy Reviews. <https://www.sciencedirect.com/science/article/pii/S2211467X19301245>; Monteiro Lunardi et al. (2018) A Review of Recycling Processes for Photovoltaic Modules. <https://www.intechopen.com/chapters/59381>

TECHNOLOGY STATE OF PLAY

Mechanical delamination technology has been demonstrated at scale overseas.

- For example, the EU's 'Full Recovery End of Life Photovoltaic' (FRELP) project, which took place from 2013-2015, utilises a four-step physical-chemical method and has demonstrated a 'high frequency knife' method at pilot scale (1,300 panels a day).[103] However, the project ceased operation due to insufficient volumes of PV waste at the time.[104] More recent projects have made progress in terms of end-to-end costs.
- More recently, the Photorama project (led by a consortium of 13 partners) in the EU is planning to pilot a diamond wire cutting delamination process followed by a second chemical delamination step.[105]

Pyrolysis or burning are also mature methods used to remove the encapsulant materials.[106]

- South Australian-based Reclaim PV (which ceased operating in 2022) adopted a less energy intensive form of pyrolysis for panel separation. The method was used alongside chemical processing for silver recovery and silicon refining, to enable recycling into the silicon supply chain.[107]
- Other thermal processes have also been developed to overcome the shortcomings of pyrolysis. For example, FLAXRES GmbH, a partner of the EU's ReProSolar project, have developed a thermal process that uses a high-intensity light pulse process for delamination.[108] The project runs from 2021 to 2025, and aims to demonstrate an industrial line with an annual capacity of 5,000 tons of modules.[109]

The chemical delamination approach is relatively less mature than the mechanical and pyrolysis pathways.

- The aforementioned Photorama (running from 2021 to 2024) project intends to demonstrate a pilot line of a two-step delamination process, applying CO2 in supercritical state ($SCCO_2$) after an initial mechanical step.[110] Supercritical CO2 is being investigated across many industries and applications as an environmentally friendly solvent.

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[103] Wang et al. (2022) A review of end-of-life crystalline silicon solar photovoltaic panel recycling technology. Solar Energy Materials and Solar Cells, 248, 111976; Tan J, Jia S, Ramakrishna S (2022) End-of-Life Photovoltaic Modules. Energies; 15(14):5113. <https://doi.org/10.3390/en15145113>; Latunussa C et al. (2016) Life cycle assessment of an innovative recycling process for crystalline silicon photovoltaic panels. Solar energy materials and solar cells. <https://doi.org/10.1016/j.solmat.2016.03.020>

[104] Heath G et al. (2020) Research and development priorities for silicon photovoltaic module recycling to support a circular economy. Nature Energy. <https://www.nature.com/articles/s41560-020-0645-2>

[105] Photorama (2022) About us. <https://www.photorama-project.eu/about-us/>

[106] Isherwood P (2022) Reshaping the Module: The Path to Comprehensive Photovoltaic Panel Recycling. <https://www.mdpi.com/2071-1050/14/3/1676>

[107] Filatoff N (2019) Australia's first solar-panel recycler plans to help green the full life cycle of components. PV Magazine, 19 January; Peacock B (2023) Weekend read: Solar recycling's glass ceiling and other problems. PV Magazine, 17 June.

[108] Flaxres (n.d.) Technology. <https://www.flaxres.com/en/technology/>

[109] Eit Raw Materials (2023) ReProSolar: Demonstrator of High Grade PV Recovery Supply chain in Europe. <https://eitrawmaterials.eu/project/reprosolar/>; Eit Raw Materials (2021) European project ReProSolar led by Veolia Germany will test full photovoltaic recycling on an industrial scale. <https://eitrawmaterials.eu/european-project-reprosolar-led-by-veolia-germany-will-test-full-photovoltaic-recycling-on-an-industrial-scale/>

[110] Photorama (2022) About us. <https://www.photorama-project.eu/about-us/>

IP activity in delamination technologies has increased sharply since 2016. However, in more recent years (from 2021) thermal and chemical delamination pathways have experienced a sharper increase in activity, relative to mechanical methods. This may reflect the shift towards higher purity recovery methods. IP capabilities across the three solar PV delamination technologies have been dominated by Asian countries who account for almost 90% of all applications. China (51%), Korea (24%) and Japan (13%) have led the way in this IP innovation, followed by the US and European countries.

The following table summarizes the key RD&D areas of focus in mechanical, thermal and chemical delamination of solar PV modules:

Table 6: Global RD&D focus areas for mechanical, thermal and chemical delamination of solar PV modules.

RD&D FOCUS AREAS	
Thermal delamination methods	• Reducing energy intensity, emissions, and release of toxic gases, while also ensuring the complete removal of the polymer encapsulant. [111]
Mechanical delamination methods	• Obtaining higher selectivity of separation between each component of end-of-life (EOL) PV.[112]
Chemical delamination methods	• Retaining intact silicon wafers for re-use, pathways to significantly accelerate the process and overcoming scale up challenges such as cost and chemicals management.[113]

3.3.2 High value metal recovery

Crystalline silicon PV panels contain metals such as silver, aluminium, copper, and silicon, making them a high value waste stream.[114] After delamination, solar cell materials are treated with reagents to separate and purify high value metals. These can then be sold as feedstock into the solar PV supply chain or into other markets.

The rationale behind recovering these components goes beyond environmental factors and extends to preserving finite resources, while also generating viable revenue streams. Solar PV manufacturers are decreasing the amounts of silver within solar panels to lower the costs of solar PV and reduce reliance on scarce minerals. Although, recycling efforts to date have focused on revenue streams from silver, in the long term the economics of recycling plants may depend on the valorisation of other material components of solar PV panels.

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[111] Deng et al. (2022) Recent progress in silicon photovoltaic module recycling processes. Resources, Conservation and Recycling <https://www.sciencedirect.com/science/article/pii/S0921344922004463>; Chouwdhury (2020) An overview of solar photovoltaic panels' end-of-life material recycling. Energy Strategy Reviews. <https://www.sciencedirect.com/science/article/pii/S2211467X19301245>; Monteiro Lunardi et al. (2018) A Review of Recycling Processes for Photovoltaic Modules. <https://www.intechopen.com/chapters/59381>

[112] Tan J, Jia S, Ramakrishna S (2022) End-of-Life Photovoltaic Modules. Energies; 15(14):5113. <https://doi.org/10.3390/en15145113>

[113] Deng et al. (2022) Recent progress in silicon photovoltaic module recycling processes. Resources, Conservation and Recycling. <https://www.sciencedirect.com/science/article/pii/S0921344922004463>; Chouwdhury (2020) An overview of solar photovoltaic panels' end-of-life material recycling. Energy Strategy Reviews <https://www.sciencedirect.com/science/article/pii/S2211467X19301245>; Monteiro Lunardi et al. (2018) A Review of Recycling Processes for Photovoltaic Modules. <https://www.intechopen.com/chapters/59381>

[114] Abdo M, El-Shazly N, Medici F (2023) Recovery of Valuable Materials from End-of-Life Photovoltaic Solar Panels. Materials (Basel, Switzerland), 16(7), 2840. <https://doi.org/10.3390/ma16072840>

The recovery of high purity silicon and other high value metals is usually done via hydrometallurgical techniques. Etching and leaching techniques are used to recover high-purity silicon of up to 6N either as an intact wafer or as a silicon powder, to be reused in high value products such as solar cells or battery anodes.[115] Here, an acid or alkaline reagent can be used to etch the surface of the silicon, or leaching can be used to remove metals from the silicon.

Hydrometallurgical methods are typically used to leach and extract silver and copper from mixed material after shredding and sorting or from intact silicon wafers. This process usually involves leaching using an acid, followed by a recovery step such as precipitation, electrolysis or metal replacement reactions to recover high purity metal from the leachate.[116]

TECHNOLOGY STATE OF PLAY

Despite limited commercial deployment, there has been significant global progress in high value metal and silicon recovery.

One example is ROSI Solar, a French start-up that is currently constructing a new industrial solar recycling plant.[117] The company's primary focus is on extracting silver and high-purity silicon using a proprietary chemical process.[118]

Australian examples include Deakin University, where researchers have demonstrated a chemical and thermal process at lab scale, converting end-of-life solar PV panels and converts them into high value nanomaterials. This method subjects recovered silicon to a special ball-milling process to produce nano-scale silicon, which is then used in the development of cost-effective battery materials.[119] UNSW, with support from ARENA, designed and demonstrated thermal delamination (pyrolysis) and hydro-metallurgical extraction of high purity metals at lab and pilot scales in 2020.[120]

As with the delamination technologies, IP activity across high value metal recovery and high purity silicon wafer and powder recovery are also concentrated in China (71%) and the Republic of Korea (18%). The US, France and Germany (7% jointly) follow in terms of numbers of patent families filed.

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[115] Deng et al. (2022) Recent progress in silicon photovoltaic module recycling processes. Resources, Conservation and Recycling https://www.sciencedirect.com/science/article/pii/S0921344922004463; Chouwdhury (2020) An overview of solar photovoltaic panels' end-of-life material recycling. Energy Strategy Reviews <https://www.sciencedirect.com/science/article/pii/S2211467X19301245>; Monteiro Lunardi et al. (2018) A Review of Recycling Processes for Photovoltaic Modules. <https://www.intechopen.com/chapters/59381>

[116] Han, Q et al. (2023) Hydrometallurgy recovery of copper, aluminium and silver from spent solar panels. Journal of Environmental Chemical Engineering, 11(1), 109236; Padoan, F. C et al. (2019). Recycling of end of life photovoltaic panels: A chemical prospective on process development. Solar Energy, 177, 746-761; Deng et al (2022) Recent progress in silicon photovoltaic module recycling processes. Resources, Conservation and Recycling. <https://www.sciencedirect.com/science/article/pii/S0921344922004463>

[117] ROSI (2023) Inauguration of the ROSI Alpes industrial plant. <https://www.rosi-solar.com/inauguration-of-the-rosi-alpes-industrial-plant/>

[118] ROSI (2023) Photovoltaic modules recycling. <https://www.rosi-solar.com/photovoltaic-modules-recycling/>; Crownhart C (2021) Solar panels are a pain to recycle. These companies are trying to fix that. MIT Technology Review. <https://www.technologyreview.com/2021/08/19/1032215/solar-panels-recycling/>

[119] Deakin University (2023) New process extracts silicon from solar panels to build better batteries. <https://www.deakin.edu.au/about-deakin/news-and-media-releases/articles/new-process-extracts-silicon-from-solar-panels-to-build-better-batteries>

[120] UNSW (2020) End-of-life, highly efficient, low-cost and eco-friendly recycling technology for silicon photovoltaic panels <https://arena.gov.au/assets/2023/03/efficient-low-cost-eco-friendly-solar-pv-recycling-technology-interim-report.pdf>

The following table summarizes the key RD&D areas of focus in high value material recovery in solar PV recycling.

Table 7: Global RD&D focus areas for high value material recovery technologies in solar PV recycling.

RD&D FOCUS AREAS	
High value material recovery	• Developing less complex, energy efficient methods that minimise the need for toxic and corrosive by-products.[121] • Optimisation of end-to-end processes from delamination through to high purity metal recovery, to improve overall efficiency, reduce overall costs, and increase recovery, product quality and revenue streams.
Infrastructure and facilities	• Development of established PV collection and recovery systems and facilities is required to enable pilot projects and scale-up.[122]

3.3.3 Implications for Australia

The high number of installed laminated panels in Australia will lead to a substantial waste stream, estimated to range from over 100,000 tonnes by 2035,[123] to a million tonnes by 2047.[124] To date the economics of solar PV recycling in Australia and globally have not been favourable. Multiple techno-economic analyses have shown that current solar PV panel recycling methods face challenging economic prospects, often requiring additional fees or process subsidisation to reach profitability.[125]

Although end-to-end, high-efficiency and high-value recovery processes are more costly than current processes, they have the potential to generate higher revenues streams by yielding higher quality products, and increasing volumes of PV waste can improve the economics of such projects.[126] This creates an opportunity for RD&D to further drive down costs, improve the efficiency of processes and increase the quality and purity of recovered materials. Several technoeconomic models have concluded that the key revenue factors included market price for materials, material quality and purity levels (particularly for glass and polysilicon), and waste volumes. A study from an independent research and business intelligence

[121] Tan J, Jia S, Ramakrishna S (2022) End-of-Life Photovoltaic Modules. Energies; 15(14):5113. <https://doi.org/10.3390/en15145113>

[122] Tan J, Jia S, Ramakrishna S (2022) End-of-Life Photovoltaic Modules. Energies; 15(14):5113. <https://doi.org/10.3390/en15145113>

[123] Sustainability Victoria (2022) National approach to manage solar panel, inverter and battery lifecycles. <https://www.sustainability.vic.gov.au/recycling-and-reducing-waste/product-stewardship/national-approach-to-manage-solar-panel-inverter-and-battery-lifecycles>

[124] Mahmoudi S et al. (2018) Material flow analysis of the end-of-life photovoltaic waste in Australia. 2018 International Conference on Energy Ecology and Environment (ICEEE 2018), DEStech Publications Inc. <https://doi.org/10.12783/dteees/iceee2018/27806>

[125] Florin et al. (2020) Scoping study for solar panels and battery system reuse and recycling in NSW. Prepared for NSW Department of Planning, Industry and Environment by UTS Institute for Sustainable Futures and Equilibrium. <https://www.epa.nsw.gov.au/-/media/epa/corporate-site/resources/grants/infrastructure-fund/isf-solar-pv-and-battery-recycling-report.pdf?la=en&hash=36F42EF246DE472E1FAD0308B4AA41E66219A139>; D'Adamo I, Ferella F, Gastaldi M, Ippolito NM, Rosa P (2023) Circular solar: Evaluating the profitability of a photovoltaic panel recycling plant. Waste Management & Research 41(6). <https://doi.org/10.1177/0734242X221149327>; Granata G, Altimari P, Pagnanelly F, De Greef J (2022) Recycling of solar photovoltaic panels: Techno-economic assessment in waste management perspective. Journal of Cleaner Production 363, 132384. <https://doi.org/10.1016/j.jclepro.2022.132384>

[126] Dias et al. (2022) High yield, low cost, environmentally friendly process to recycle silicon solar panels: Technical, economic and environmental feasibility assessment. Renewable and Sustainable Energy Reviews, 169, 112900; Deng R, Chang NL, Ouyang Z, Chong CM (2019) A techno-economic review of silicon photovoltaic module recycling. Renewable and Sustainable Energy Reviews 109, 532-550. <https://doi.org/10.1016/j.rser.2019.04.020>

company estimated that the value of recyclable materials from EOL solar PV panels could reach over US$2.7 billion in 2030, growing from the estimated $170 million in 2022.[127]

International state of the art, end-to-end recycling pilot projects have shown steadily increasing rates of material recovery, from roughly 60% in 1998, to about 96% in 2016, and have transitioned from the recovery of bulk materials, to targeting high-value metals.[128] Technoeconomic analyses of end-to-end high value recycling processes are difficult to conduct due to the lack of industrial scale plants and the differences in recycling processes. Piloting different processes and engaging in knowledge sharing internationally can help build certainty around technical parameters and costs.

This section discusses the opportunities for domestic RD&D and international engagement in solar PV recycling (summarised in Figure 16). More details on the framework used can be found in the main report *From minerals to materials: Assessment of Australia's critical mineral mid-stream processing capabilities.*

Figure 16: Opportunities for Australian RD&D and international engagement in solar PV recycling.

Opportunity area	Establish new capability in emerging technologies	Accelerate emerging technologies and grow Australian IP	Pilot and scale up Australian IP	Support commercial deployment of mature technologies
Applicable Technologies			• Solar PV recycling	
RD&D actions	Build capability in emerging technology areas via fundamental and applied research projects.	Leverage Australia's strengths to progress technologies beyond the lab and grow Australian IP.	Deploy Australian IP in pilot-scale and commercial-scale demonstrations.	Support the deployment of mature technologies domestically at commercial scale, through commercial testing and validation, and cross-cutting RD&D.
International engagement actions	Engage with research institutions on capability building and knowledge sharing (e.g. joint research programs).	Partner with overseas industry, research or government on mutually beneficial sustained technology development efforts (e.g. co-funded or joint projects).	Engage with upstream offtakers to de-risk and finance pilot projects. Alternatively, demonstrate Australian technologies overseas.	Engage on commercial arrangements e.g. international technology providers, license overseas patents, attract foreign direct investment, and secure offtake agreements.

IP, intellectual property; PV, photovoltaic.

Australia has several comparative advantages with respect to developing and scaling up end-to-end high value solar PV recycling. As mentioned previously, high volumes of PV waste are important for the economic viability of a plant. Australia's high uptake of solar PV is a key advantage for a future commercial scale recycling facility. Victoria, South Australia and the ACT have banned disposing of solar panels in landfills, mandating that they have to be dropped off at dedicated e-waste collection points for recycling. This can help divert the volumes required for the commercial viability of PV recycling projects in Australia. However further development is required to ensure a robust collection system is established. Patent trends indicate Solar PV recycling is an emerging and growing area of RD&D activity globally. Given Australia has undertaken several projects in this space, there is potential to continue to grow capability, and to build domestic IP.

RD&D in delamination technology is a clear enabler for better processing of PV waste in Australia, as it is the first step to high value metal recovery. However, the choice of delamination technology will ultimately depend on several factors; the target product quality and therefore the revenue stream it generates; and the overall cost and sustainability of the end-to-end recycling process. Conventional mechanical pathways such as crushing pathways are able to process high volumes of waste relatively fast but are not suitable for

[127] Rystad Energy (2022) Reduce, reuse: Solar PV recycling market to be worth $2.7 billion by 2030. <https://www.rystadenergy.com/news/reduce-reuse-solar-pv-recycling-market-to-be-worth-2-7-billion-by-2030>

[128] Deng et al. (2019) A techno-economic review of silicon photovoltaic module recycling. Renewable and Sustainable Energy Reviews, 109, 532-550.

the recovery of intact silicon wafers and can lead to more difficult separation overall.[129] However, they can make second-stage delamination using heat or chemicals more effective. Conversely, mechanical methods that keep the wafer intact (e.g., hot knife method) can be cost-effective and enable wafer recovery. Given the solar industry trend towards manufacturing thinner silicon wafers, mechanical methods could become increasingly challenging with respect to wafer brittleness.[130]

Mature delamination pathways such as pyrolysis are effective at removing the encapsulant, however can be highly energy intensive (and therefore costly), can release toxic gases, and can lead to wafers breaking in the process, making this a less suitable option for approaches aiming to recover intact silicon wafers.[131] However, newer thermal pathways are being developed to overcome some of the drawbacks of pyrolysis. Examples include two-step pyrolysis technologies that eliminate toxic gases, and alternative thermal techniques that combine thermal and physical methods (e.g. laser irradiation and 'hot knife' methods).[132]

Chemical delamination routes tend to have a trade-off between the toxicity or concentration of the chemicals and their emissions, versus the speed and effectiveness of encapsulant removal process. The cost of reagents can also be an issue.[133] However, many of these trade-offs can be overcome by pairing less aggressive chemical processes with other techniques to enhance separation such as ultrasound, microwave or supercritical CO_2.[134]

Due to the emergence of delamination and the similar levels of maturity between each delamination pathway, progressing pilot demonstrations of different technologies can help identify the best pathway forward. Given that several pilot projects are already occurring overseas it will be essential for Australia to engage in knowledge sharing with partners and avoid duplication of RD&D investment. Learnings and data from overseas projects should be assessed for the Australian context. Considerations for the Australian context include applicability of technologies to the dominant panel types in Australia, electricity prices, availability of chemical feedstocks, and transport costs.

RD&D in high value metal recovery can enable resource circularity, unlock greater revenue streams from high value waste, and alleviate supply bottlenecks for scarce metals. RD&D in this area can also help reduce technology costs and overcome technical barriers to scale up. As the solar industry moves towards using less silver in next generation modules, revenue streams focused solely on silver recovery may diminish in the longer term. Processes that can commercially valorise multiple components (e.g., silicon, glass, copper, aluminium and silver) will be important. The recovery of higher purity materials like glass and polysilicon could also increase the financial viability of solar panel recycling by directly attracting higher price points,[135]

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[129] Isherwood P (2022) Reshaping the Module: The Path to Comprehensive Photovoltaic Panel Recycling. <https://www.mdpi.com/2071-1050/14/3/1676>; Deng R et al. (2022) Recent progress in silicon photovoltaic module recycling processes. <https://www.sciencedirect.com/science/article/pii/S0921344922004463>

[130] Isherwood P (2022) Reshaping the Module: The Path to Comprehensive Photovoltaic Panel Recycling. <https://www.mdpi.com/2071-1050/14/3/1676>

[131] Deng et al. (2022) Recent progress in silicon photovoltaic module recycling processes. Resources, Conservation and Recycling. <https://www.sciencedirect.com/science/article/pii/S0921344922004463>; Wang et al. (2022) A review of end-of-life crystalline silicon solar photovoltaic panel recycling technology. Solar Energy Materials and Solar Cells, 248, 111976; Tan J, Jia S, Ramakrishna S (2022) End-of-Life Photovoltaic Modules. Energies; 15(14):5113. <https://doi.org/10.3390/en15145113>

[132] Wang et al. (2022) A review of end-of-life crystalline silicon solar photovoltaic panel recycling technology. Solar Energy Materials and Solar Cells, 248, 111976.

[133] Deng et al (2022) Recent progress in silicon photovoltaic module recycling processes. Resources, Conservation and Recycling <https://www.sciencedirect.com/science/article/pii/S0921344922004463>

[134] Wang et al. (2022) A review of end-of-life crystalline silicon solar photovoltaic panel recycling technology. Solar Energy Materials and Solar Cells, 248, 111976.

[135] Deng R, Chang NL, Ouyang Z, Chong CM (2019) A techno-economic review of silicon photovoltaic module recycling. Renewable and Sustainable Energy Reviews 109, 532-550. <https://doi.org/10.1016/j.rser.2019.04.020>

or by supporting higher-value manufacturing processes. For instance, if a sufficiently high quality of silicon is recovered from solar PV waste, it could be used as a feedstock into solar grade silicon (or polysilicon) production, or for other markets such as lithium batteries. If the silicon recovered is solar grade (6N or above), then it has the potential to bypass the Siemens process to produce solar modules at significantly lower energy input than from raw materials.[136]

Cross-cutting areas that will be important to support the development of these technologies in Australia include lifecycle analysis, techno-economic modelling of end-to-end recycling systems, waste stream data and market data collection and analysis, and the evaluation and development of e-waste standards and collection systems.

[136] Huang W et al. (2017) Strategy and technology to recycle wafer-silicon solar modules. Solar Energy. <https://doi.org/10.1016/j.solener.2017.01.001>

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