November 2022

Australian Silicon Action Plan

pwc

CSIRO

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Acknowledgements

We acknowledge and pay our respects to Aboriginal and Torres Strait Islander peoples as the First Peoples of Australia, whose ancestral lands and waters we work and live on throughout Australia. We honour the wisdom of, and pay respect to, Elders past, present and future.

Scope of the report

The scope of the report agreed with CSIRO is to develop a report on the opportunity for Australia to develop an integrated silicon and solar cell supply chain.

The information, statements, statistics and commentary (together the Information) contained in this report has been prepared by PwC.

The Information used to prepare this report has been sourced from:

- PwC research using publicly available material referenced in footnotes
- inputs from the CSIRO as our client
- information obtained through market consultations conducted with 10 industry stakeholders and participants involved throughout in the silicon supply chain in Australia and internationally
- the Silicon and Polysilicon Report prepared by CRU International Ltd for the CSIRO.

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Foreword

CSIRO has been studying the likely impact of the coming energy transformation, especially as it concerns the minerals that are critical to generation and storage. Our Critical Energy Minerals Roadmap and subsequent analysis has not only highlighted the increasing need for solar photovoltaic technology, and therefore silicon, as critical to decarbonisation, but revealed that there was a concentration risk in the silicon supply chain. As such, we commissioned two independent pieces of work to confirm our initial findings and to guide our thinking about the next steps to take.

The first of these was CRU Consulting's 2022 Silicon and Polysilicon Report. We are pleased to share some of CRU's findings, which are embedded in this PricewaterhouseCoopers report, the Australian Silicon Action Plan.

It is clear from these findings that there is considerable merit in growing Australia's participation in the silicon supply chain. This supply chain starts with our endowment of high-quality quartz, which can be processed to metallurgical grade silicon, then to solar grade polysilicon. This supply chain is an essential enabler of the energy transition in a supply-concentrated market.

The Australian Silicon Action Plan lays out achievable steps that we can take as a nation, or in collaboration with our trading partners, and will serve as a reference point for researchers, industry and government.

Dr Chris Vernon

CSIRO Critical Minerals Leader

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Executive summary

The global deployment of solar power technology will be critical to the success of the global energy transition. By 2050, solar and other renewables will be the leading source of energy generation globally.[1] The energy transition is accelerating at scale and at pace, and geopolitical tensions and the COVID-19 pandemic have highlighted the fragility of Australia's current supply chains and the risks associated with highly concentrated energy supply chains.

Australia has world-leading solar resources and a vast land mass that will allow us to facilitate deployment at scale. These advantages must be leveraged to meet Australia's national targets of cutting emissions by at least 43% by 2030 and reaching net zero by 2050, enable the export of energy to other countries to help achieve their net zero goals and establish a local green hydrogen industry of global significance. It will require a rapid and large-scale escalation in solar power installations and there will be challenges ahead.

1 Achieving energy independence is a priority for the Australian Government, given disruptions and risks in the global macroeconomic environment. Yet Australia is entirely reliant on overseas supply chains for solar cells. The current supply chain for solar cells – the technology required to generate solar power – is highly concentrated.

2 The focus on environmental, social and governance (ESG) matters and a desire for transparency means the solar cell supply chain – the production of silicon and polysilicon and the manufacture of high-technology solar cells – is under greater scrutiny. The current supply chain poses ESG risks, including the carbon footprint arising from its high energy intensity, and modern slavery issues, that contribute to the urgent need for Australia to act.

3 Australia is currently in danger of missing out on the economic and social benefits that local manufacturing and value-added industries could bring in the silicon and solar cell supply chains.

But with those challenges come opportunities. Australia has immense potential to develop more of the silicon and solar cell supply chain locally. However, given the current supply chain risks and the pace of solar uptake required, Australia needs to act strategically, collaboratively and quickly to:

- improve and stabilise our supply chain security and energy independence
- develop new industries with high ESG operating standards
- create economic benefits for future generations.

The ultimate vision is for an integrated silicon and solar cell supply chain, including recycling to address end-of-life considerations, that is powered by renewable energy and creates truly circular outcomes. Although this vision will take time to be realised, Australia must start working towards it today.

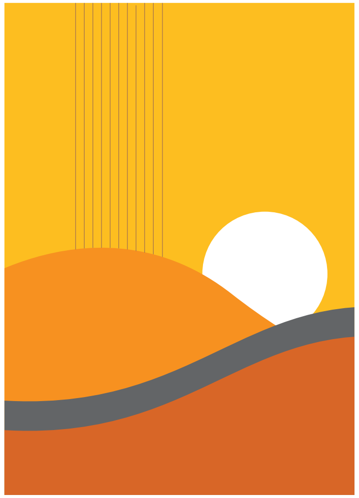
This Australian Silicon Action Plan (ASAP) outlines actions that will improve Australia's current position. of minimal supply chain activity and dependence on overseas supply chains for solar cells. It focuses on the silicon supply chain input into solar cells, one key input of solar photovoltaic projects. Building capacity in silicon is an opportunity for Australia to improve its energy independence, given the prevailing concentration and geopolitical risks.

The ASAP is organised into three horizons, which consider both time and technology. **Horizon 1: Silicon production** outlines clear and achievable actions that can be taken today that focus on expanding Australia's capacity in silicon production. This will create optionality and momentum for the actions set out in **Horizon 2: Solar cell manufacturing** and **Horizon 3: Integrated supply chain**.

All stakeholders in the solar cell ecosystem have a role to play. The ASAP outlines practical steps for government, industry and research organisations to make progress on the journey to an integrated supply chain and associated energy independence outcomes that will create economic and social benefits for Australia.

[1] *IEA, Executive summary of special report on solar PV global supply chains, IEA, 2022.*

Australian Silicon Action Plan



Horizon 1

Silicon production

Horizon 1 outlines actions to develop Australia's silicon production industry. This is the first step on the journey to an integrated silicon and solar cell supply chain.

Incentivise the supply of raw materials and build silicon production capacity in Australia

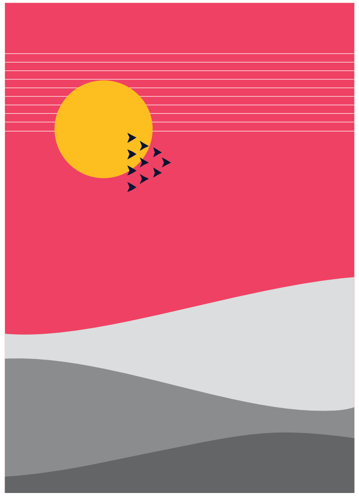
- Action 1: Establish an industry standard for quartz quality for use in the solar cell supply chain
- Action 2: Integrate renewable energy generation and energy recovery into the silicon production process
- Action 3: Ensure that solar project developers and operators share the development risks and benefits

Catalyse initial growth

- Action 4: Fund and establish test facilities to support the silicon industry
- Action 5: Phase in 'local content' incentives for new solar project developments
- Action 6: Adopt a 'market–maker' role with international partners
- Action 7: De-risk new supply chain development through targeted funding support

Investigate next-generation processes and technologies

- Action 8: Develop alternative reductants for silicon smelting and investigate next-generation processes and technologies
- Action 9: Participate in related international R&D initiatives

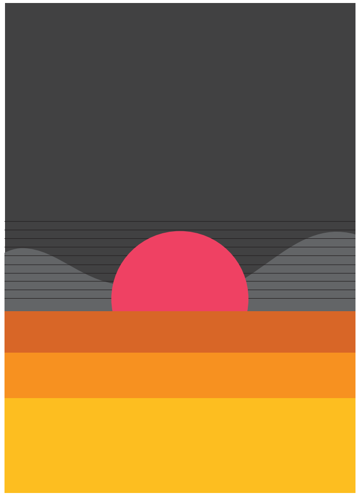


Horizon 2

Solar cell manufacturing

Horizon 2 actions are focused on expanding Australia's supply chain activity. This expansion incorporates the development of additional domestic silicon production capacity, transitioning into ingot, wafering and cell manufacturing, and continuing to fund relevant R&D activities.

- Action 1: Develop ingot, wafer and solar cell manufacturing capabilities
- Action 2: Invest in module manufacturing and recycling initiatives
- Action 3: Explore and assess emerging technologies

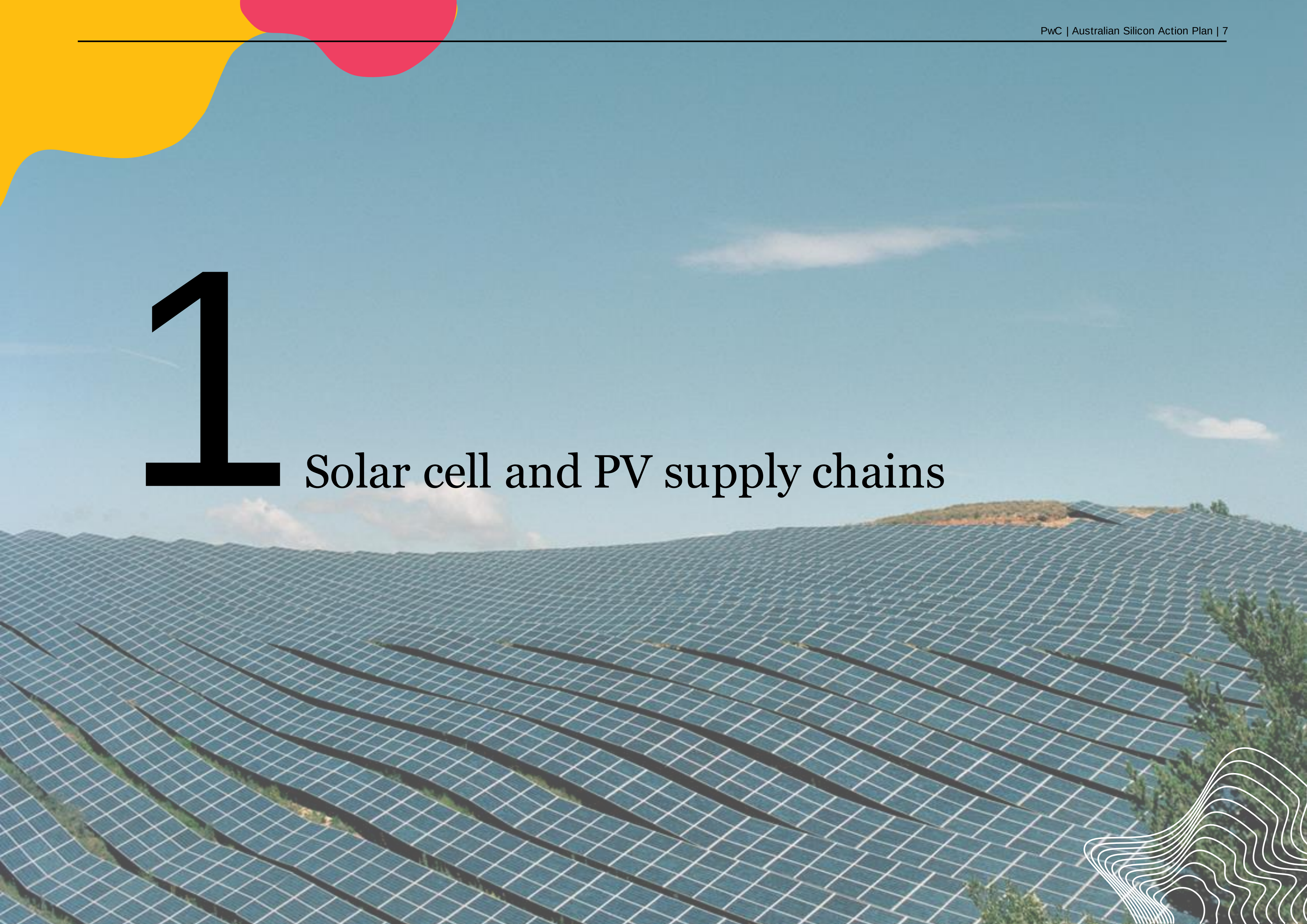


Horizon 3

Integrated supply chain

Horizon 3 outlines actions to move to an integrated, low-carbon and circular solar cell supply chain in Australia.

- Action 1: Develop polysilicon manufacturing capabilities
- Action 2: Focus R&D efforts on developing and scaling up emerging and future technologies



1 Solar cell and PV supply chains

Solar will be a dominant energy source in the future and the technology is underpinned by silicon

The energy transition is happening at scale

The race to net zero will rely on the rapid uptake of solar photovoltaic (PV) technology. Renewable technologies will generate 90% of the world's electricity by 2050, with solar PV the leading technology. The International Renewable Energy Agency (IRENA) has estimated that annual global solar power generation capacity must increase from the current level of 1 terawatt (TW) to 5.2 TW by 2030 and 14 TW by 2050 to stay on track to meet the Paris Agreement's emissions goals (Figure 1).[2]

The role and importance of solar PV will increase dramatically if the world's green hydrogen ambitions are to be realised in the coming decades. The Australian Energy Market Operator (AEMO) put Australia's solar requirements at 360 gigawatt (GW) by 2050 in the 'Hydrogen Superpower' scenario in their flagship annual document, the 2022 Integrated System Plan (ISP).[3]

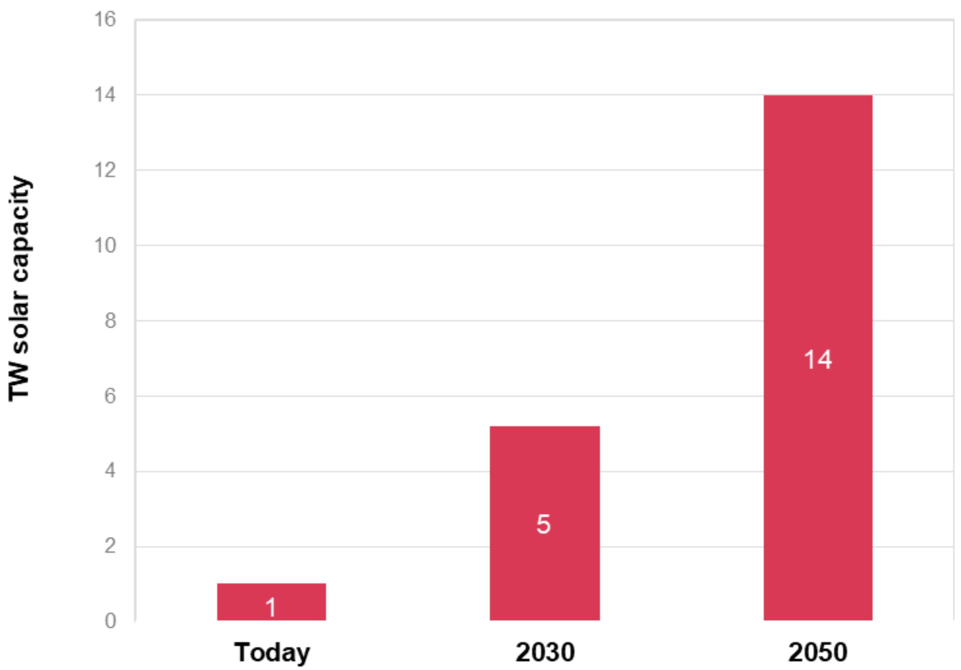
Australia has a genuine opportunity to emerge as a global superpower in solar PV energy generation and export. We have the highest per capita deployment of rooftop solar in the world – a great start. We also have world class solar resources and significant areas of land available for large-scale solar arrays.

However, one of the greatest risks to Australia's solar ambitions and energy independence is our complete reliance on overseas supply chains for solar cells. Silicon, the critical mineral required for solar cell technology, has a highly geographically concentrated supply chain. This creates significant risks for the cost, reliability, and timeliness of new solar developments.[4]

It would be highly desirable – both economically and geopolitically – for Australia to develop its own capability and capacity in the solar cell supply chain. This must begin with the production of silicon and progressively integrate more of the solar cell supply chain locally.

Silicon (Si) is a chemical element that makes up over one-quarter of the Earth's crust, although it does not occur naturally in its pure metallic form. Silicon occurs as silicon dioxide (SiO_2), in both rock form (quartz) and granule form (silica sand). Silicon, as an element, is used in a range of commercial applications, including solar PV panels, electronic chips (semiconductors), aluminium alloying, silicones and optical fibre.

Figure 1: Global solar power generation



Source: IRENA, World Energy Transitions Outlook 2022: 1.5°C Pathway.

Silicon is a strong semiconductor that is resistant to corrosion and non-toxic to the environment. This, along with its abundance, makes it the most practical material to use in solar cells.

Over 90% of solar cells are made of a specific type of silicon called photovoltaic-grade silicon or crystalline polysilicon (polysilicon).[5] Polysilicon is a processed and highly refined form of silicon.

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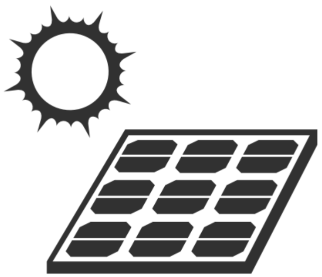
[2] IRENA, World energy transitions outlook 2022: 1.5°C pathway, IRENA, 2022, p. 66, accessed 28 September 2022.
[3] AEMO, Integrated system plan for the National Electricity Market: June 2022, AEMO, 2022, accessed 28 September 2022.
[4] IEA, Special report on solar PV global supply chains, IEA, 2022, pp. 8-9, 54, accessed 28 September 2022.
[5] CRU, Silicon and Polysilicon Report, CRU, 2022, p. 10.

The solar cell and solar panel supply chains carry geographic concentration risk

To understand why Australia needs to develop its own solar PV supply chain capacity, it is important to understand the steps and processes in the global supply chain for silicon and solar cells, from quartz extraction to module assembly (Figure 2).

The ASAP focuses on the solar cell supply chain, from quartz to cell manufacturing and eventual recycling. Solar cells represent one component of solar panels, and its key inputs are silicon and polysilicon.

This differs from the wider solar PV supply chain which, while including silicon and solar cells, also includes aluminium, solar glass, silver, junction boxes and other components required to develop a solar PV project.



A schematic of a solar module consisting of nine solar cells

Figure 2: Solar PV supply chain and its geographic concentration

Stage	Description	Major producers
Quartz extraction	• Mining of high-quality quartz deposit • Quartz (SiO_2) is geologically common, but requires specific levels of purity for optimal use in the solar cell supply chain	Geographically diverse
Silicon smelting	• Smelting process to separate silicon from oxygen and create silicon • Carbon source (coal, charcoal) required in reaction • High temperature process requiring significant energy input	70% in China, 7% in Brazil, 7% in Norway
Polysilicon production	• Complex metallurgical processing of silicon to achieve high levels of purity for end use in solar cells • High energy and heat requirements • Capital intensive	79% in China, 8% in EU, 6% in rest of Asia
Ingots, wafers and cells	• Process of 'melting' polysilicon in cylindrical crucibles (ingots) and thinly slicing material into wafers • Further processing (doping, coating, testing) • Manufacturing into solar cells	85-97% in China, 3-12% rest of Asia, 0-1% India
Module assembly	• Assembly of solar cell with other solar PV supply chain components (backsheet, glass, frame) into a solar PV module	75% in China, 15% rest of Asia, 3% India
End use	• Installation of solar PV into end-use PV systems and applications – mounting, grid connection • High growth across all global regions	
Module recycling	• Current estimated service life of 20 to 30 years • End-of-life and circular economy capabilities can relieve pressure on primary supply industries • Technical and economic challenges can be overcome	

Sources: IEA, Special report on solar PV global supply chains; CRU, Silicon and Polysilicon Report; PwC analysis.

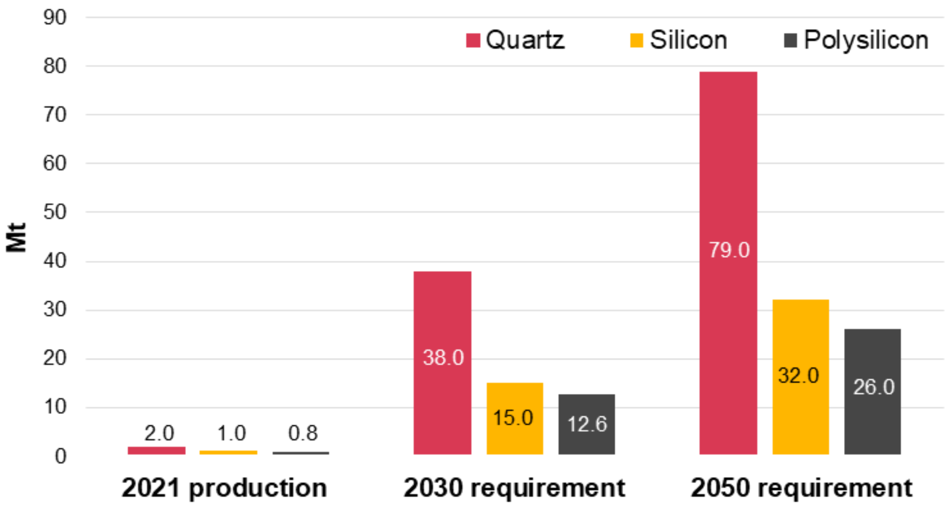
Silicon and polysilicon production needs to scale to meet solar demand growth

To reach net zero by 2050, the world will need much more polysilicon than is currently being produced.

It is estimated that by the end of 2021 global polysilicon production capacity reached approximately 750 kilotonne (kt).[6] The current global solar capacity is estimated as 1 TW.

To keep pace with the demand from solar alone, based on IRENA's forecast of 5.2 TW of global solar capacity needed by 2030, annual global production of polysilicon will have to more than double from 0.8 megatonnes per annum (Mtpa) to 1.8 Mtpa over the period 2023 to 2030 (Figure 3).

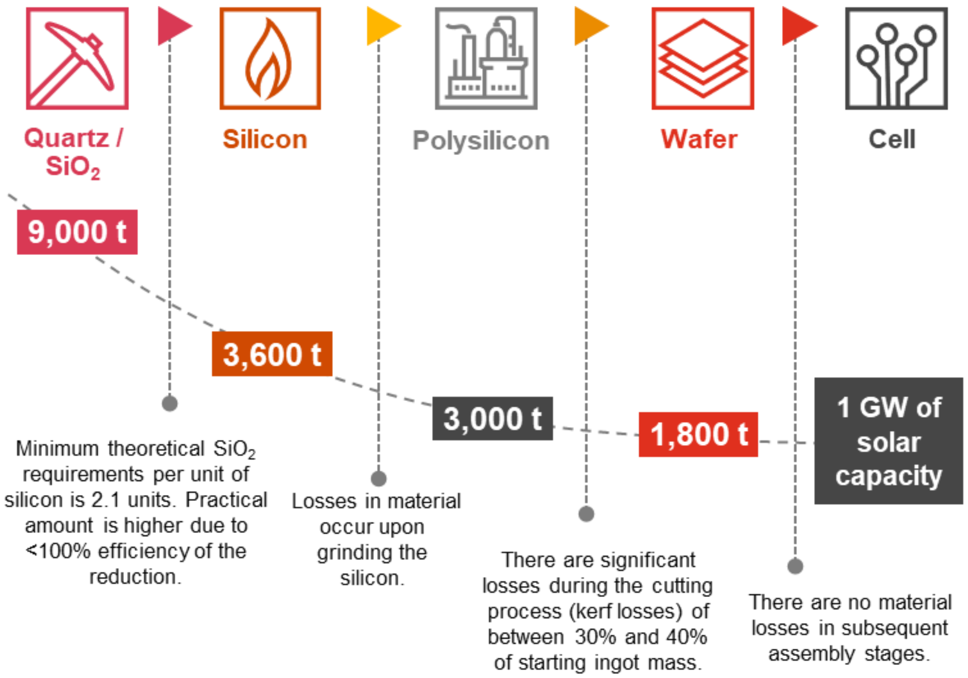
Figure 3: Total tonnage of silicon products to meet solar energy requirements



Note: Quartz and silicon production are estimates of the volume required to produce polysilicon in any given year. This analysis does not include quartz and silicon production for other (non-polysilicon) markets.

Sources: IRENA, World Energy Transitions Outlook 2022: 1.5°C Pathway; PwC analysis and market research.

Figure 4: Silicon loss in the supply chain process



Sources: IEA, Special report on solar PV global supply chains, p. 22; CRU, Silicon and Polysilicon Report, p. 72; PwC analysis.

[6] *IEA, Special report on solar PV global supply chains, p. 22.*

The solar cell supply chain begins with quartz extraction

To be suitable silicon feedstock, quartz must be 'lumpy' (meaning it is sourced from rock, rather than sand), and be approximately 3–10 cm in diameter.

Silica sand is not suitable for an electric arc furnace as the grains would be packed too tightly together, reducing the efficiency of the process.

Silica sand is suitable for solar panel glass but not cells.

The suitability of a quartz deposit for silicon feedstock depends primarily on two qualities:

1. **Thermal stability** – The quartz must be able to retain its structural integrity in the upper zones of the silicon furnace under the heat and pressure of the smelting process to facilitate the reaction processes involved in extracting the silicon.
2. **Chemical purity** – The quartz must have sufficient purity levels in its natural form. Generally, this level is between 99.2% and 99.8%, but this will depend on the presence of specific impurities (e.g. phosphorous, iron or boron), which are difficult to remove downstream.

Figure 5: Quartz purities

Name	Purity (SiO_2 concentration)
High quality quartz (i.e. suitable for industrial applications that include solar cells)	99.2% – 99.8%
Specialty glass quartz	99.8% – 99.99%
High-purity quartz (HPQ) (IOTA® 4 and 5) – uses including crucibles for solar applications	99.995% – 99.998%

Sources: CRU, Silicon and Polysilicon Report; PwC analysis.

Quartz purity

There is some confusion about the purity level of quartz required for use as feedstock in the solar cell and PV supply chain.

Two major quartz companies operate a single quartz asset in North Carolina, USA, that provides much of the world's high-purity quartz for specialty end-use markets. Sibelco, one of the companies, has established an industry benchmark for quartz purity, known as the IOTA® standards, which has set a standard for high purity quartz (HPQ). HPQ, as defined by this standard, is required for some specialty end-use products like electronics and crucibles that are used to shape ingots.

However, this level of purity is not required to produce silicon and manufacture solar cells (Figure 5). Establishing a new industry standard – high quality quartz – for other industrial end uses, like solar, would be useful and sensible.

'Purity' refers to the chemical purity of the SiO_2 by weight, but this cannot be viewed in isolation and the types of impurities present must be considered to assess quartz viability for further processing.

Silicon smelting requires specific inputs of energy, carbon and quartz

Quartz undergoes a reductive smelting process in a submerged electric arc furnace to produce silicon.

In the furnace, the quartz is subjected to a high temperature (greater than 2000°C). The carbon reductant reacts with the quartz, causing the carbon atoms to bind to the oxygen in the silicon dioxide. This isolates the silicon and creates CO_2 as a by-product (Figure 6).

The silicon that is produced has a purity level of about 99.0% to 99.6% by weight, which is suitable as feedstock for the solar cell supply chain.

Figure 6: Silicon smelting inputs and outputs

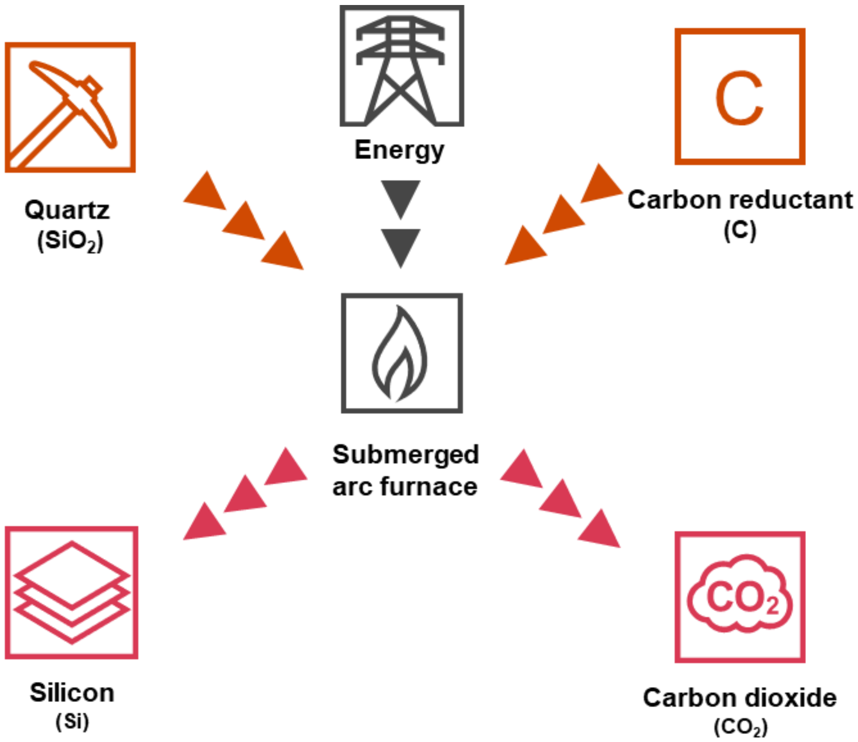


Figure 7: Key elements of the silicon smelting process

Quartz

Once extracted, quartz needs to be ground to specific size specifications (ideally about 30 mm to 100 mm) for optimal use in the smelter. Quartz that is too fine does not react suitably in the smelter and larger quartz lumps react too slowly.

Electrodes

Electrodes conduct electricity through the furnace, which provides the high temperatures required for the smelting process. Electrodes are made from carbon, typically graphite or a composite carbon material. Electrodes are depleted with use and are a key cost and input for silicon production.

Energy

The silicon smelting process is energy intensive. Achieving and maintaining high temperature requires a large and reliable source of power. Approximately 12 kilowatt hours (kWh) of energy per 1 kg of silicon output is required. A standard 50 kilotonne per annum (ktpa) silicon plant requires 570 gigawatt hours (GWh) per year (at 95% utilisation).

Reductant

The reductant is a key component in the smelting process. It is usually sourced from coal or charcoal. The optimal reductant depends on the existing impurities in the quartz feedstock, to get the right 'mix' in the submerged arc furnace for the target specification of the final product. Market standard has been low ash coal due to its reactivity and low impurities, but new options are emerging. The optimal reductant source is often a mix of both coal and charcoal.

Sources: CRU, Silicon and Polysilicon Report; PwC analysis.

Silicon is further purified to polysilicon before its use in ingots and wafers

Polysilicon

Silicon undergoes further processing and purifying to create polysilicon. Polysilicon to be used in the solar PV supply chain requires purity levels of between 6N and 10N. The most common purification method is hydrochlorination synthesis, known as the 'Siemens process'.

This is the most technically advanced step of the solar PV supply chain, which carries accompanying safety risks. The energy requirements for polysilicon production are approximately 100 kWh per kg of polysilicon produced, also making it the most energy intensive step of the supply chain.[7] This process is over six times more energy intensive than aluminium smelting and eight times more energy intensive than silicon smelting.

Polysilicon production facilities are also capital intensive, having the highest construction costs in the solar PV supply chain (Figure 8).[8] Based on available estimates, a greenfield 60,000 tonne per annum (tpa) polysilicon plant being constructed in a Western economy could have pre-production capex between US$2.5bn and US$4bn.[9]

Polysilicon purity

The purity of polysilicon is measured using N notation. The number preceding the N represents the number of 'nines' in the percentage or decimal fraction.

Solar cells require polysilicon purity of between 6N (99.9999% pure) and 10N (99.99999999% pure). Semiconductors require polysilicon purity of 9N to 11N.

However, the most recent greenfield plant constructed had a total cost of over US$100 per tonne (t) of capacity, implying a cost of over US$6bn for a 60 ktpa equivalent polysilicon plant.[10]

Ingots

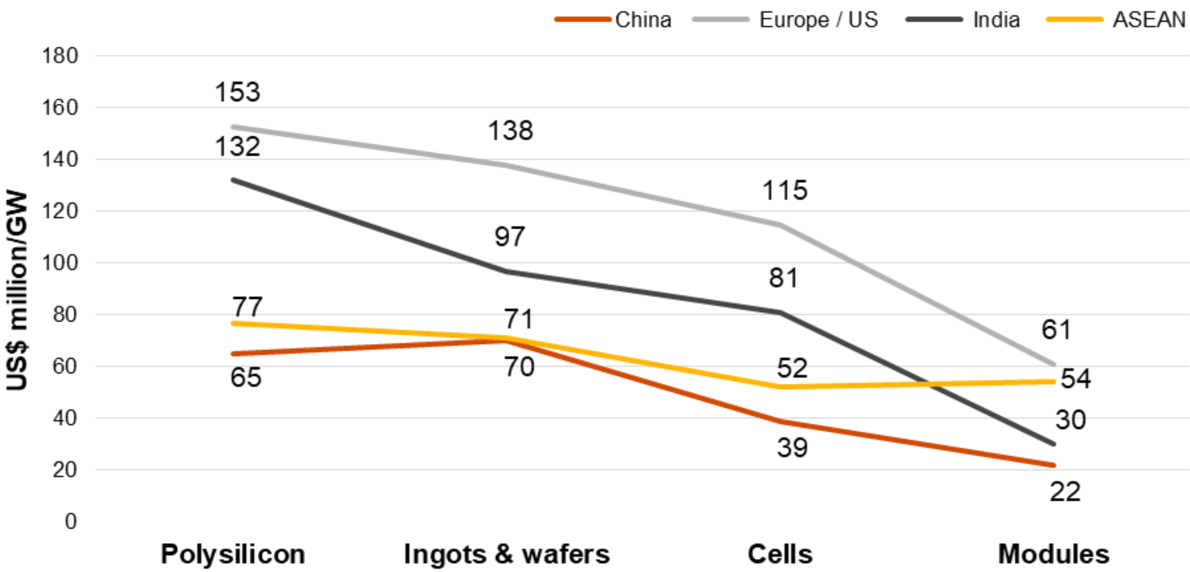
Polysilicon is melted and reshaped into cylindrical ingots. The ingots are 'doped' with boron or phosphorous, which strengthen their electrical properties and increase the amount of energy they can generate from sunlight.

Wafers

Ingots are sliced into thin wafers that form the core component of solar cells. Solar cells require very thin wafers – typically around 0.16 mm.[11]

The conversion of polysilicon into ingots and wafers is energy intensive, with high and precise heat requirements that are similar to those for silicon smelting.[12]

Figure 8: Capital investment requirements by value chain segment



Source: IEA, Special report on solar PV global supply chains.

[7] *CRU, Silicon and Polysilicon Report, p. 119 . This is a high-level value and not for any specific operating or proposed plant. Energy consumption data for polysilicon plants are dealt with secretively.*
[8] *Basore P and Feldman D, Solar photovoltaics: supply chain deep dive assessment, National Renewable Energy Laboratory, Department of Energy, US, 2022, accessed 28 September 2022.*
[9] *Low end: Ibid; high end: CRU, Silicon and Polysilicon Report, CRU, p. 138.*
[10] *CRU, Silicon and Polysilicon Report, p. 123.*
[11] *ibid. p. 48.*
[12] *IEA, Special report on solar PV global supply chains, pp. 7–12.*

Cells are assembled into solar modules

Solar cells

While there are several types of solar cell technology, with different manufacturing methods, all commercial cells are manufactured from polysilicon wafers. The purity of polysilicon wafer input has a direct effect on the efficiency and material requirements of the cell.

The solar cells are soldered together and arrayed onto a polymer back sheet, which protects the solar cells from the environment and ensures that panels remain electrically insulated.

Solar modules

The cells are coated in a specialised glass layer that allows light to pass through while providing protection. This is framed by aluminium racks, which both protect the edges of the cells and provide a solid structure to form a solar module, or panel.

Recycling

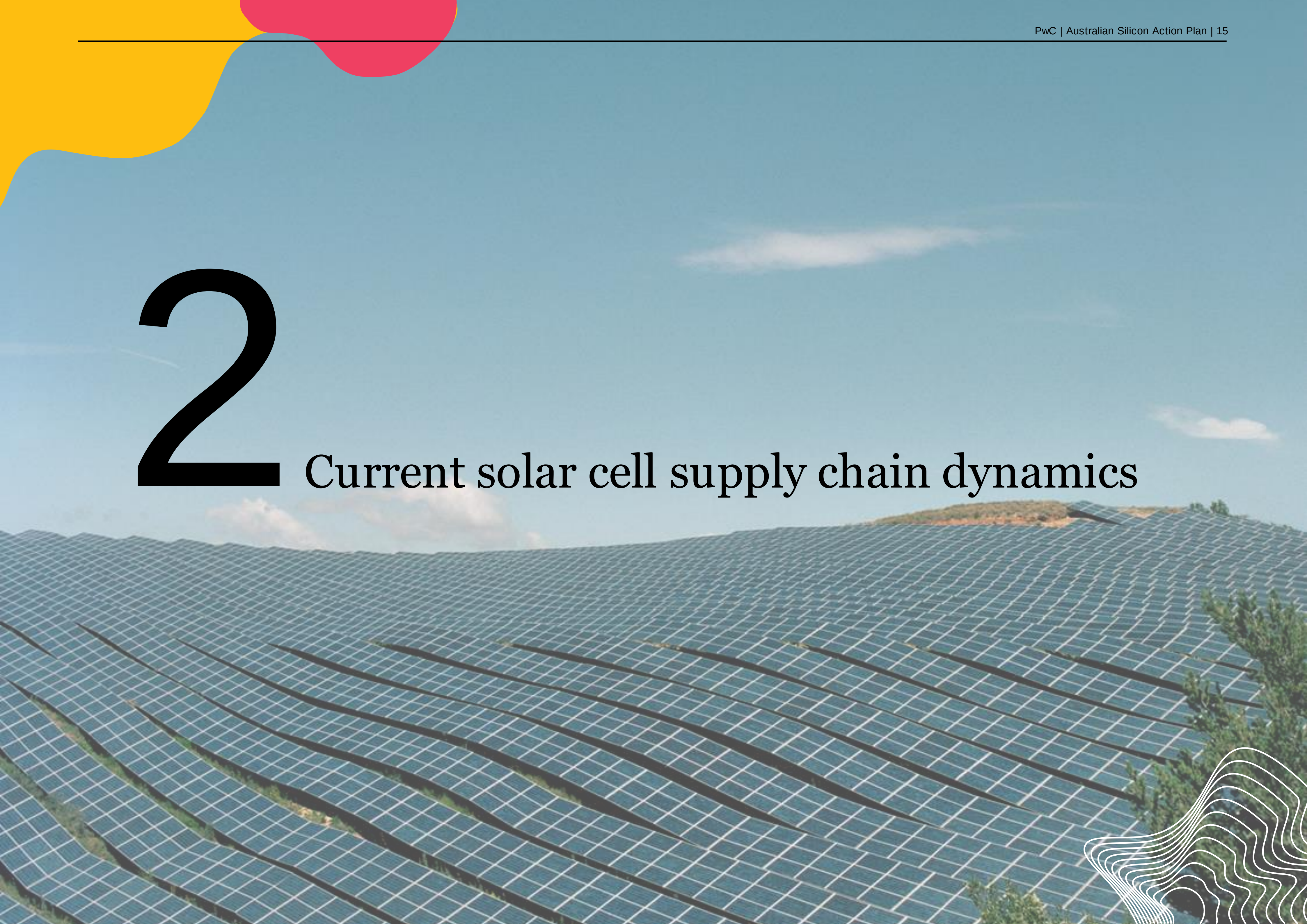
The global solar panel recycling industry is still developing, as panel recycling has not yet reached critical mass (given their 25 to 30-year lifespan) and current panel designs are focused on reducing manufacturing costs, rather than component separability.

However, with the value of each recycled panel potentially exceeding A$20/panel,[13] environmentally responsible module design and recycling is an untapped opportunity for the industry.

Methods for recycling panels vary and are evolving, but will broadly include the following steps

1. separation of the aluminium frame and junction box
2. removal of the glass from the silicon cell through thermal, mechanical, or chemical processes, uncoupling of the silicon cells and specialty metals (e.g. silver, copper) through chemical and electrical processes
3. uncoupling of the silicon cells and specialty metals (e.g. silver, copper) through chemical and electrical processes.

[13] *IEA, Special report on solar PV global supply chains, p. 100.*



2 Current solar cell supply chain dynamics

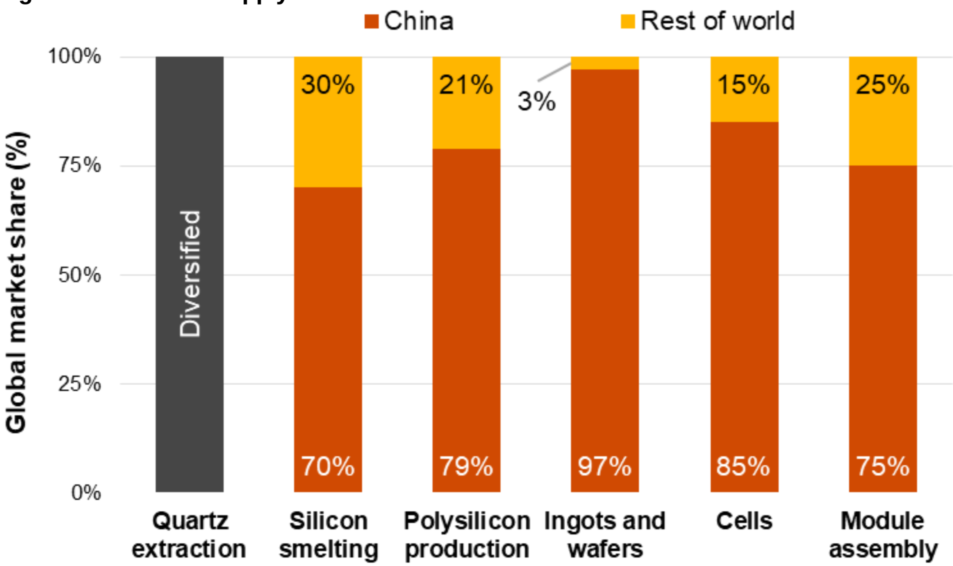
Supply chain concentration is a risk for Australia's decarbonisation efforts and energy independence

Multiple factors are contributing to a fundamental shift in global production processes and supply chains.

Geopolitical tensions, natural disasters, climate change, energy market issues and the COVID-19 pandemic have highlighted the fragility of our current supply chains and the risks associated with supply chain concentration.[14]

In 2021, around 70% of silicon was produced in China.[15] China also dominates the production of polysilicon, with the small balance of production occurring in Germany, the USA and Malaysia. The conversion of polysilicon to assembled solar modules is even more concentrated, with China accounting for between 75% and 97% of these stages of production (Figure 9).[16]

Figure 9: Solar PV supply chain concentration



Sources: IEA, Executive summary of special report on solar PV global supply chains; CRU, Silicon and Polysilicon Report, p. 106; PwC analysis.

Geographically concentrated supply chain activity exposes participants to key risks arising from:

- changes in diplomatic relations among and between countries
- vulnerabilities in the dominant supplier's policies and infrastructure
- potential for export restrictions from the dominant supplier.

These risks are in addition to the multiple factors mentioned (geopolitics, climate change, energy market issues) already contributing to the shift in global supply chains.

The concentration in the solar cell supply chain impacts the availability and cost of solar cells and is a key risk to Australia's energy independence and decarbonisation efforts. Concentration risk is also impacting solar project developers seeking to rely on bank debt or capital markets, as financiers are increasingly focused on supply chain transparency and resilience.

Addressing these risks requires a rebalancing of global supply chain activity toward regional networks or among strategic allies and trading partners (Figure 10).

Figure 10: Recently announced supply chain domestication policies

Country	Measure	Date
USA	The Solar Energy Industries Association sets target of 50 GW of solar manufacturing production by 2030	Aug 2022
USA	US$56m government funding boost to spur PV manufacturing domestication	July 2022
EU	The European Commission's EU Innovation Fund signed its first solar grant agreement for PV cell manufacturing capability to accelerate its energy transition and reduce reliance on external capability	Early 2022
India	Production Linked Incentive (PLI) scheme, with the aim of increasing domestic manufacturing and reducing import dependence in the renewable sector, particularly in the earlier stages of the supply chain (i.e. Si-PV production stage)	April 2021

Source: PwC analysis.

[14] PwC, Building rebalanced and resilient supply chains, PwC, 2022, accessed 28 September 2022.
[15] CRU, Silicon and Polysilicon Report, p. 8.
[16] IEA, Executive summary to the special report on solar PV global supply chains.

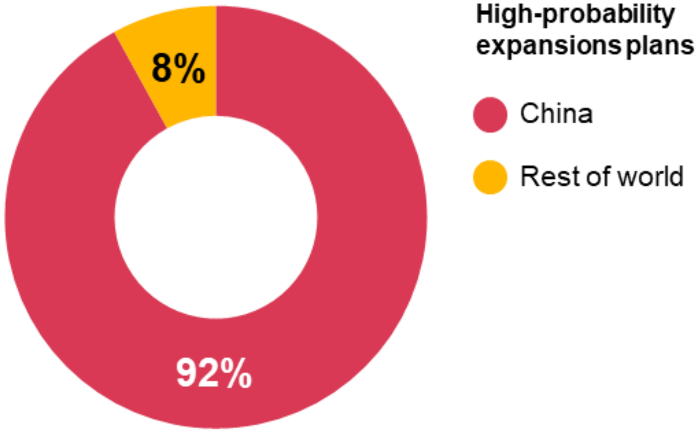
Currently planned polysilicon capacity growth will exacerbate concentration risks

Polysilicon supply disruptions

Concentrated supply chains are prone to natural and technical disasters. In 2020, an explosion at a polysilicon facility in China put 8% of global polysilicon production capacity out of operation. This was the largest of four polysilicon plant closures that occurred in 2020 due to flooding and technical issues. Each incident occurred at a different time and together led to an estimated 4% decline in annual production in what is already a tight polysilicon market. This contributed to prices almost tripling between 2020 and 2021. In July 2022, a fire at a polysilicon facility in Xinjiang and the subsequent maintenance reduced global production by 0.5%, which contributed to further price increases.[17]

Annual polysilicon production must double in the coming decade to meet expected solar PV demand.[18] There are several polysilicon expansion plans in the global pipeline, but over 90% of new production is currently expected to occur in China (Figure 11). This narrowly based expansion will only exacerbate the concentration risk.

Figure 11: Polysilicon capacity expansion



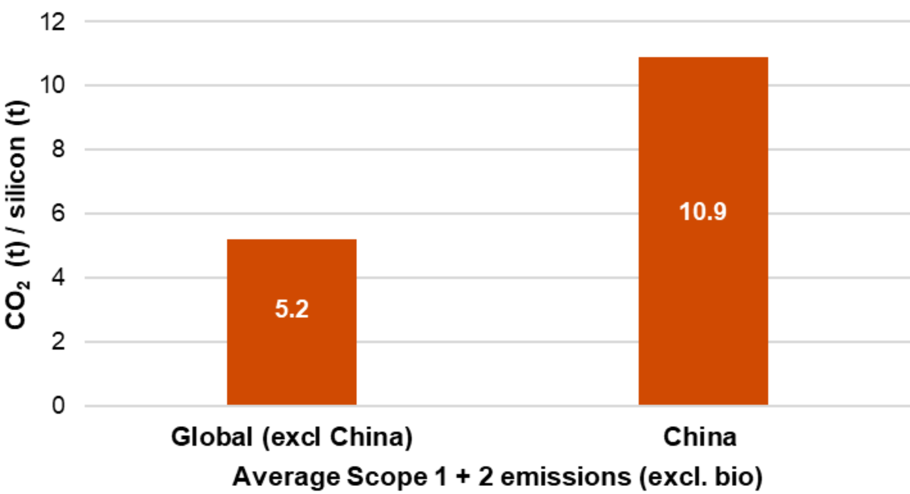
Source: CRU, Silicon and Polysilicon Report, Tables 55 and 56.

Emissions

The International Energy Agency (IEA) estimates that the global average carbon intensity of solar PV manufacturing is 270 kg CO_2/kW capacity.[19]

The process of turning high quality quartz into silicon and polysilicon requires large amounts of heat, pressure and electricity to break chemical bonds and remove impurities. Much of the production in China relies on brown coal for energy, resulting in significant emissions (Figure 12). Due to the supply chain concentration, the volume of panels that are transported (and the distances they travel) to end users contributes to the overall carbon footprint of the supply chain. Emissions from these exports accounted for over 62% of all module export–related emissions worldwide.[20] Shorter or more localised supply chains will result in lower emissions. Alternative and cleaner sources of energy for the silicon and polysilicon processes will require changes to existing processes and will entail additional costs.

Figure 12: Emissions in the solar PV supply chain



Source: CRU, Silicon and Polysilicon Report, p. 130. (Note: biogenic emissions have been excluded from the emissions intensity curve as they can be considered carbon neutral).

[17] *IEA, Special report on solar PV global supply chains, p. 60.*
[18] *Ibid.*
[19] *Ibid., p. 78.*
[20] *Ibid., p. 44.*

Differences in labour practices are a concern for solar developers, presenting an opportunity for Australia

The solar supply chain is highly labour intensive. The IEA estimates that 1,300 manufacturing jobs are required for each GW of production capacity (across the full supply chain).[21] Labour demands broadly increase further along the supply chain and vary depending on the type of factory, levels of automation and the extent to which operations have been streamlined.

In 2020, it was estimated that almost 2.3 million people were employed in the solar PV industry in China, including in the Xinjiang region in Western China.[22] In August 2022, the United Nations released findings of a multi-year investigation into allegations of human rights abuses in this region.[23] Xinjiang is currently the predominant solar manufacturing province in China – the US Department of Energy estimates that this region alone hosts 39% of global solar manufacturing.[24]

In Australia, there is an increasing awareness of the social benefits of applying ethical sourcing principles across the supply chain and introducing appropriate labour protections, both of which underpin ethical labour practices.[25]

From a labour perspective, there are two benefits of establishing an Australian silicon and solar cell supply chain: there are already established labour protections in place, and it would create new clean energy economy jobs in value-added processing and manufacturing.

> “Addressing climate change is not only an opportunity for more jobs, it represents an obligation to ensure that those jobs pay decent wages, have good conditions, and deliver better lives for ordinary workers. We face a collective endeavour that is almost of unprecedented scale. We need to mine, move and manufacture immense volumes of material, energy and equipment. We need to train and mobilise hundreds of thousands of skilled blue- and white-collar workers to fill new, good-quality jobs.”
>
> The Hon Chris Bowen MP,
> Minister for Climate Change and Energy[26]

[21] IEA, Special report on solar PV global supply chains, p. 94.
[22] REN21, Renewables 2022 global status report, REN21 Secretariat, Paris, 2022, p. 58, accessed 28 September 2022.
[23] Office of the High Commissioner for Human Rights, OHCHR assessment of human rights concerns in the Xinjiang Uyghur Autonomous Region, People's Republic of China, United Nations, 2022, accessed 28 September 2022.
[24] US Department of Energy, Solar photovoltaics supply chain deep dive assessment, US Department of Energy, 2022, p. 26, accessed 6 October 2022.
[25] Office of the High Commissioner for Human Rights, OHCHR assessment of human rights concerns in the Xinjiang Uyghur Autonomous Region, People's Republic of China.
[26] Center for Strategic & International Studies (CSIS), Toward a clean and secure energy future in the Indo-Pacific: A conversation with Australian Minister for Climate Change and Energy Chris Bowen, CSIS 2022, accessed 23 September 2022.

Key messages about the solar cell supply chain

1

Australia's energy independence is at risk due to current supply chain concentration

- Energy independence is a priority for Australian governments and the solar cell supply chain currently exhibits concentration and ESG risks. The increasing pace of the energy transition, as well as the uncertain macroeconomic environment, have highlighted the fragility of our current supply chains and created urgency for Australia to become more energy independent.

2

The supply chain is complex and energy intensive

- The supply chain from the extraction of quartz to the production of a solar cell is complex, involving many stages with different technical, resource and capital requirements. At each step in the process there are factors that must be considered to ensure financial and operational viability. Capability at one stage is not necessarily indicative of capabilities required at other stages of the supply chain. Building capacity in one supply chain step creates the option for further integration of other parts of the supply chain.
- The energy required (and how it is produced) throughout the supply chain is an essential consideration, particularly in relation to silicon and polysilicon production.

3

Economic opportunities abound in the new energy economy

- Expanding Australia's silicon and solar cell supply chain has the potential to crystallise economic opportunities to Australia, through the creation of a new industry and new jobs in value-added and manufacturing industries, including in regional areas.

4

Operating standards are under greater scrutiny

- With an increased focus on ESG globally, Australia can be a pioneer in supporting a low-carbon silicon supply chain.
- Australia has expertise in the construction of renewable energy projects and an abundance of land and sun to support new projects. These significant advantages can be used to provide the lower emissions power required for the energy-intensive stages of the silicon and polysilicon supply chain.

3 Australia's existing supply chain capabilities

Developing a silicon and solar cell supply chain is an opportunity Australia must grasp immediately

Solar will be the dominant energy source in Australia in the future, with significant investment being made to develop large-scale projects. Ensuring reliability and certainty of supply will be paramount to Australia being able to meet its solar power aspirations.

Demand for solar power

Australia has committed to solar power being a cornerstone of its decarbonisation efforts. Between 2021 and 2050, solar PV's contribution to the energy mix in Australia is expected to increase from 12%[27] to approximately 50%.[28] Across the National Energy Market (NEM),[29] the current pipeline of announced and committed utility-scale projects is over 43 GW, which is more than 1.5 times the national installed solar capacity of 27 GW.[30]

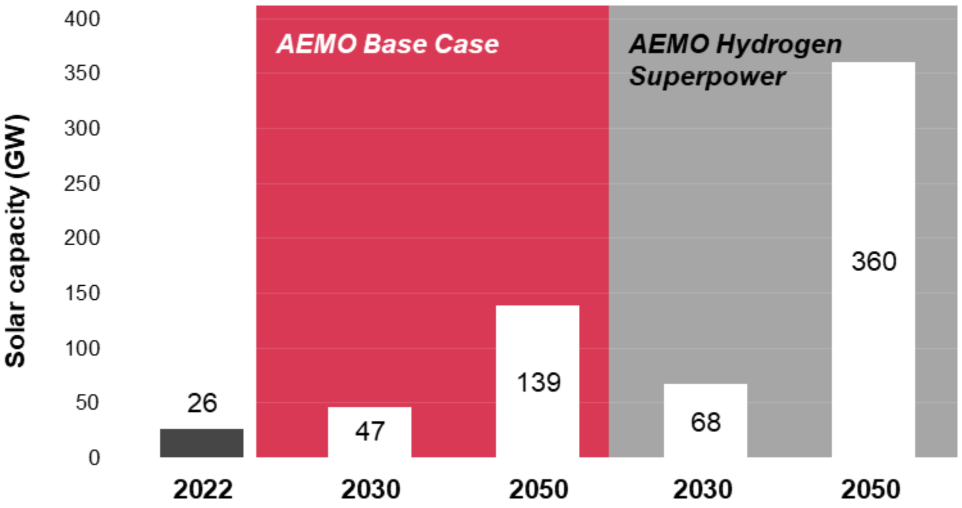
In the Step Change scenario (i.e. base case) outlined by the AEMO, the combined solar generation capacity of the NEM and future solar projects will be 139 GW, while under its 'Hydrogen Superpower' scenario, solar generation capacity will reach 360 GW by 2050 (11 times the national installed solar capacity in mid-2022) (Figure 13).

Demand for silicon

The case for silicon goes beyond solar. New energy transition applications are emerging, particularly in silicon use in battery anodes, and these may have enormous impacts on the demand profile for silicon. Under the IEA's Sustainable Development Scenario, silicon demand has the potential to increase by a factor of 460x between 2020 and 2040 if silicon-doped graphite battery anodes increase their market share from 1% to 15% over the same period (Figure 14).

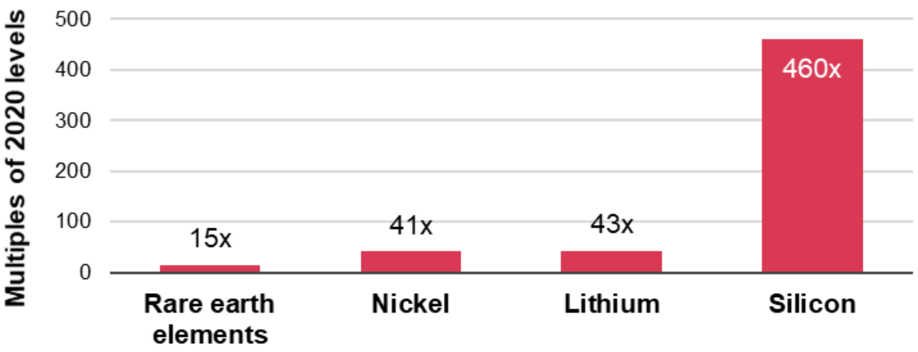
Given Australia's commitment to solar energy as a pillar of our energy transition, and the potential growth in demand for silicon from other energy transition technologies, we should be investing now to develop our domestic capabilities in extracting quartz and processing silicon, as well as evaluating other opportunities across the solar PV supply chain.

Figure 13: Australian demand for solar power



Source: AEMO, Integrated system plan for the National Electricity Market: June 2022.
Note: The graph only contemplates NEM capacity per the ISP, and does not include major, large scale off-grid pipeline projects.

Figure 14: Estimated 2040 demand for metals



Source: IEA, The role of critical minerals in clean energy transitions, IEA, 2022.

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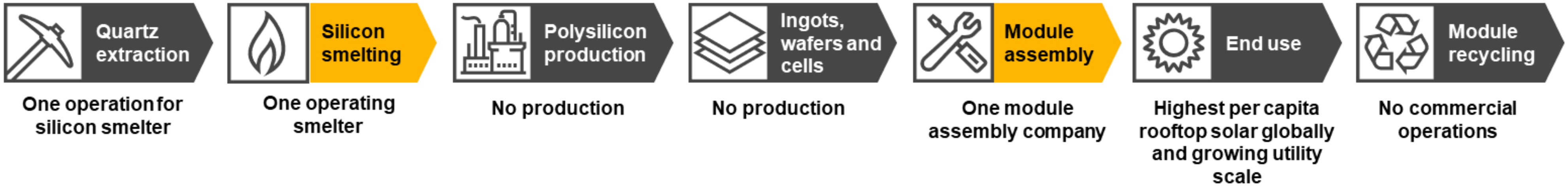
[27] *CEC, Clean Energy Australia Report 2022, CEC, 2022, p. 10, accessed on 28 September 2022.*
[28] *AEMO, Integrated system plan for the National Electricity Market: June 2022.*
[29] *The NEM covers NSW, South Australia, ACT, Victoria, Queensland, and Tasmania.*
[30] *AEMO, NEM Generation Information August 2022, AEMO, 2022, accessed 28 September 2022.*

Australia’s solar PV supply chain capabilities are currently limited, but opportunities abound

Figure 15: Australian current solar supply chain



Case study: SIMCOA

The only producer of silicon in Australia is SIMCOA Operations, a wholly owned subsidiary of Shin-Etsu Chemical Co (Japan). In 2021, SIMCOA produced approximately 1.7% of global silicon output. [31]

Although SIMCOA benefits from several advantages that would not be available to a new Australian entrant – for example, a global parent and decades of operational experience, this case study provides insights into the value of high-quality inputs and processes, and the advantages of having a dedicated and viable smelting operation.

SIMCOA mines its own quartz for smelting at its facility in Western Australia and operates its own charcoal production facility at its smelter, using locally sourced native timber residues and plantation blue gum together with charcoal imported from Indonesia.[32] SIMCOA is reliant on imported low-ash coal from Colombia as a reductant source, which is supplemented by locally sourced charcoal. SIMCOA also has relatively streamlined, automated processes, employing 175 people in its 45,000 tpa facility. A comparable operation in China would employ approximately four times that number of staff. [33, 34]

SIMCOA has a silicon recovery rate [35] of around 87% due to its high-quality raw materials, the use of charcoal as a reductant and general process improvements that have been introduced since its operations started in 1989. China’s silicon recovery rate averages around 75%, due to lower-quality inputs and process controls. [36]

Case study: Tindo Solar

Australia’s only solar panel assembly and manufacturing company is Tindo Solar. It operates a 150 megawatt (MW) capacity facility in Adelaide, South Australia.

Tindo received early support from the SA Government, which mandated that a large-scale battery storage trial must source solar panels from Australia, an instance of local procurement requirements incentivising new industry.

Tindo has also integrated renewables into the manufacturing plant through power purchase agreements.

Recycling and circular economy considerations

It is estimated that more than 100,000 t of solar panels will enter Australia’s waste stream by 2035.[37]

The Australian Government established the *Product Stewardship Act 2011*, which provides a framework and accreditation program for recycling. Solar panel waste was added to this legislation in 2016, but the current legislative landscape for solar panel recycling requires further development. A dedicated PV Working E-stewardship Group was set up in late 2021 by state governments to ‘progress the establishment of product stewardship solutions for solar panels while also providing an information-sharing forum amongst government officials, for broader e-stewardship reforms and projects across Australian jurisdictions’.[38] However, management and disposal of solar waste still varies by state – Victoria is currently the only state that has categorised solar panels as e-waste, meaning panels are banned from ending up in landfill. A national approach is needed.

There has been recent advancement in Australia’s solar recycling industry, in anticipation of increased volume. The first recycling plant was completed in late 2020 in Melbourne and two new facilities are planned in Adelaide and Brisbane.

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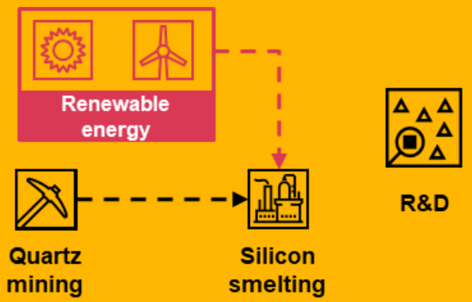
[31] *CRU, Silicon and Polysilicon Report, p. 10.*
[32] *Ibid., p. 88.*
[33] *SIMCOA, Simcoa website, accessed 20 September 2022.*
[34] *CRU, Silicon and Polysilicon Report, p. 106.*
[35] *Recovery rate refers to the ratio of actual silicon output relative to the theoretical output possible.*
[36] *CRU, Silicon and Polysilicon Report, p. 94.*
[37] *Sustainability Victoria, National approach to manage solar panel, inverter and battery lifecycles, Sustainability Victoria, 2022, accessed 28 September 2022.*
[38] *ANAO, Australian Government Implementation of the National Waste Policy Action Plan, ANAO, 2022, accessed 28 September 2022.*

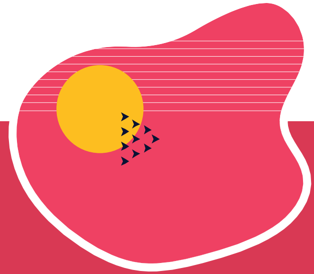
4 The ASAP vision

The vision is for Australia to develop a fully integrated silicon to solar cell supply chain

Horizon 1: Silicon production

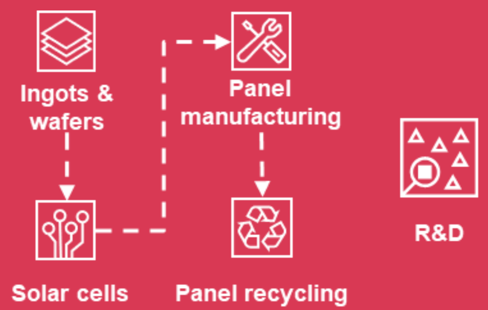
The first step is to expand capacity in quartz extraction and silicon smelting, maximising renewable energy to power the smelting process. It is critical that Australia establishes a presence on the supply chain, and these actions can be taken immediately.

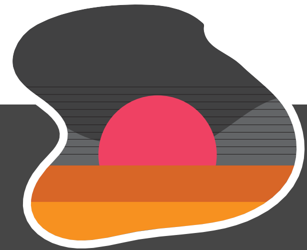




Horizon 2: Solar cell manufacturing

Building on the foundations of Horizon 1, and through collaboration with allies, Australia should work to break the geographic concentration of ingot, wafer and cell manufacturing, and increase its module manufacturing and recycling capabilities.





Horizon 3: Integrated supply chain

Production of polysilicon in Australia is a longer-term ambition, due to cost, energy intensity, technical capability and potential for substitution. In the meantime, the focus should be on R&D and coordinating strategic partnerships with international polysilicon producers that can improve supply chain security.

Activating and executing the ASAP will unlock potential across Australia's energy transition

- Australia's solar requirements for net zero and energy transition
- Collaboration with international partners regarding offtake agreements, technology developments and free trade
- Developments in high-growth battery technology applications for silicon
- Energy transition ambitions rely on domestic solar capacity, including the green hydrogen export industry
- Australian solar powers the silicon and solar cell supply chain, including end-of-life and recycling, creating truly circular outcomes
- Australian exports of silicon to our trading partners and allies

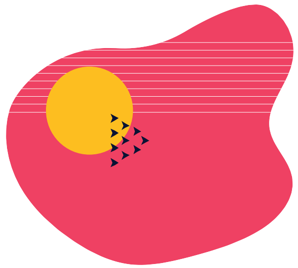
Progress towards an integrated supply chain can be achieved over 3 horizons

The vision for Australia is for a fully integrated silicon and solar cell supply chain to be developed, from quartz mining through to manufacturing, end-of-life processes and recycling, to support and de-risk the overall solar PV supply chain.

The goal is for the entire supply chain to be low carbon, with smelting, processing and manufacturing industries powered by renewable energy, creating truly circular outcomes.

The key to realising this vision will be the continued decarbonisation of Australia's energy grid and innovation in the solar supply chain, such as new reductants for silicon smelting and new processes for module recycling. Australia's highly skilled workforce and research and development capabilities will also be critical to supporting this transition.

However, this is a challenging vision to realise. It will require collaboration among all stakeholders. The necessary actions have been broken down into three horizons, each of which takes into consideration time, cost and technology.



Horizon 2
Solar cell manufacturing

Horizon 2 actions are focused on expanding Australia's supply chain activity.

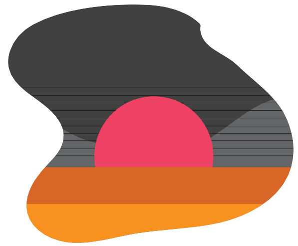
This expansion incorporates the development of additional domestic silicon production capacity, transitioning into ingot, wafer and cell manufacturing, and continuing to fund relevant R&D activities. Horizon 2 does not follow the supply chain linearly but focuses on areas that Australia can most feasibly target over the medium term, bearing in mind cost, complexity and existing industrial capabilities. This will require Australia to source polysilicon offshore over the medium term.

Horizon 1
Silicon production

Horizon 1 of the ASAP outlines near-term actions to initiate the staged development of an integrated silicon and solar cell industry.

It is the first step on the journey to develop an integrated silicon and solar cell supply chain. Horizon 1 focuses on incentivising the expansion of silicon production capacity in Australia, while focusing R&D efforts on technologies that will support Australia's silicon and supply chain industries.

The actions laid out in Horizon 1 are achievable and can be commenced immediately.



Horizon 3
Integrated supply chain

Horizon 3 outlines actions to move to an integrated, low-carbon and circular solar cell supply chain in Australia.

Horizon 3 activities would follow completion of the actions in Horizons 1 and 2. An important consideration prior to embarking on Horizon 3 activities would be the level of progress with the metallothermic reduction process (see Horizon 1, Action 9). A technology breakthrough with this process, and effective commercialisation and deployment at scale, might enable the substitution of the current polysilicon production step in the supply chain. For this reason, and the current overall cost and complexity, polysilicon production is included in Horizon 3.

Horizon 1 – Domestic quartz mining and silicon production will get Australia on the right track

Incentivise the supply of raw materials and build domestic silicon production capacity

Developing quartz resources, reductant supply options and silicon production capacity are the most logical and achievable immediate actions.

Australia has high-quality quartz resources and several existing projects in the development pipeline. Currently, the largest hurdle to developing these projects successfully is finding offtakers for the quartz. This is essential to finance and construct a new mine.

Australia must develop its own silicon smelting capacity to build the nation's potential for additional supply chain activities, while enhancing trade relationships with strategically aligned nations.

Taking these initial actions has the potential to deliver the following benefits:

1. Initiate the domestication of the silicon and solar cell supply chain
2. Support Australia to achieve its energy transition goals
3. Enhance Australia's energy security
4. Create options for further supply chain development to be exercised over Horizons 2 and 3.

Horizon 1 – Prioritise regions in Australia best suited for quartz and silicon production

Smelter location considerations

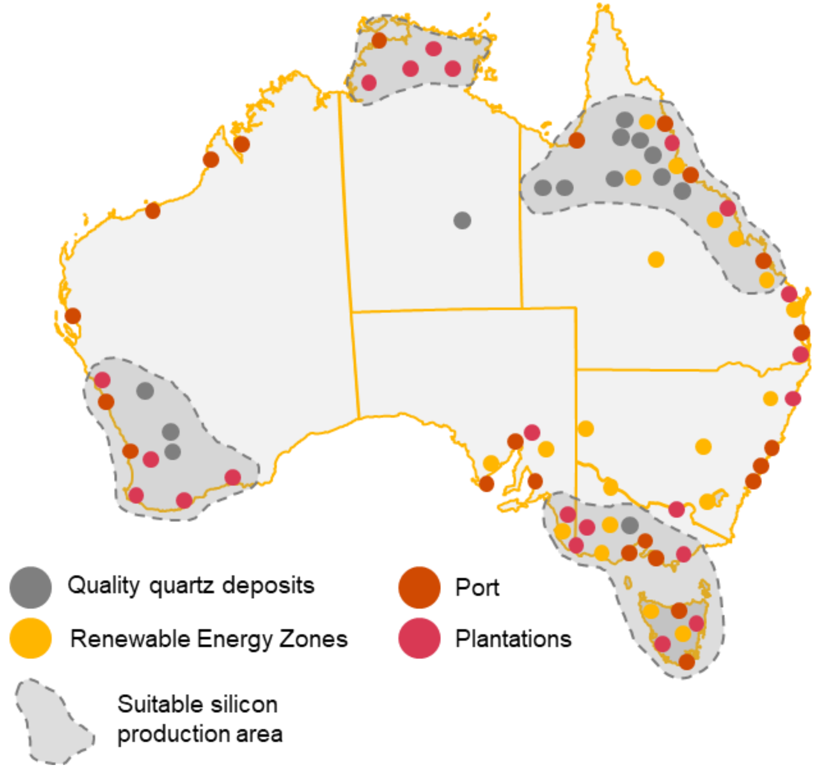
The silicon smelting process is energy intensive. This makes proximity and access to sources of affordable and reliable power an important consideration when establishing new smelting facilities in Australia. Matching renewable energy with storage capacity will support the reliability requirement and enhance the decarbonisation goal.

Shared facilities among stakeholders in the silicon ecosystem will be key to the development of the industry. Solar cell manufacturing precincts could support businesses to attract labour, arrange renewable energy agreements, streamline development approval processes and gain economies of scale with enabling infrastructure (Figure 16).

Priority	Consideration	Comments
1	Energy supply	Low-cost, reliable and 'green' energy is critical to silicon production, given the energy intensity of the process. Access to clean energy is essential for developing Australia's silicon capacity. Proximity to energy generation should be prioritised to minimise transmission losses. Locating smelters near existing and/or planned renewable energy zones should be a key consideration.
2	Reductant supply	Proximity to a source of reductants is another key consideration. Locating smelters near a sustainable source of carbon (charcoal or an alternative carbon source) is important to minimise transport costs and maintain reductant efficiency.
3	Access to skilled labour	Access to skilled labour will support efficient operations. If available, local labour will contribute to regional development. Process efficiency and skilled staff are essential to manage the process of silicon production.
4	Quartz supply	Quartz does not deteriorate with time or conditions and shipping costs generally form a small percentage of overall costs for a smelter. The location of deposits is therefore less important than the location of energy and reductant supplies. Quartz of the necessary quality for silicon production is not scarce – Australia has several known deposits.

Australia has several potential sites for silicon production. Many of these are in regional Australia and are close to oil, gas and coal projects. Given the need for skilled labour and port facilities, silicon production has the potential to create regional employment and support workforce transition from fossil fuel industries. Stakeholder engagement and consultation must be a core component of any new quartz and silicon project development.

Figure 16: Potential Australian locations



Source: PwC analysis and market research.

Note: Western Australia is not supplied by the NEM and does not have formal renewable energy zones equivalent to the eastern states.

Horizon 1 – Establish a quartz purity industry standard and integrate renewable energy

Action 1: Establish an industry standard for quartz quality for use in the solar cell supply chain

It is recommended that an industry body or government agency with oversight of the resources industry takes responsibility for defining new standards for quartz quality in Australia. The new standards should:

- separate the concept of high purity quartz from the IOTA® standards
- use clear language, with reference to 'solar-grade quartz' or 'high-quality quartz'
- clarify why silica sand is unsuitable as a feedstock for the solar cell supply chain.

These changes will provide clarity for new entrants in quartz extraction and silicon production.

Action 2: Integrate renewable energy generation and energy recovery into the silicon production process

Given the energy intensity of the smelting process, it is essential to integrate renewable energy generation into new operations to reduce the carbon footprint of the supply chain.

A silicon smelter with a capacity of 30 ktpa (slightly smaller in size than the SIMCOA facility) operating at 95% capacity consumes approximately 340 GWh of energy per year, or as much as about 70,000 Australian households.[39,40] With energy being the largest cost in operating a smelter, and with a desire to decarbonise, renewable energy supported by storage capacity must be at the centre of establishing Australia's silicon production industry.

This can be achieved by:

- installing silicon furnaces that can be ramped up and down without impacting the smelting process, allowing the smelter to respond to available renewable energy
- co-locating smelters with a Battery Energy Storage System to help manage the intermittent nature of renewable energy generation
- exploring 'provider-of-last-resort' options with a gas connection or base-load power from the grid.

A silicon smelter in Australia could be supported by renewable energy supplied through a power purchase agreement (PPA).

Power purchase agreements

A PPA is an agreement by an offtaker (e.g. a silicon producer) to purchase renewable energy from an energy generator at an agreed price for an agreed period. Australia has a highly developed and competitive PPA market. Renewable energy developers seek offtakers with strong credit ratings to lower the cost of capital for the funding required to develop their projects.

Developers of renewable energy projects will seek out high-quality offtakers to reduce the risk associated with the development of their projects and attract debt funding at competitive margins. New silicon producers are likely to have to demonstrate consistent operations before they are viewed as low-risk, long-term offtake for energy. Once operating, the high load factor and long-term commitment should be viewed as attractive for energy generators.

To reduce barriers to investment, and to initiate the industry, all governments could assist in reducing the risk to energy generators who are contracting to an early-stage silicon market entrant by:

- supporting the development of renewable energy generation projects in regions suitable for silicon production (e.g. by accelerating planning approvals and grid connection agreements)
- underwriting a portion of the debt funding for developers of renewable energy projects (e.g. through the establishment of specific funding schemes)
- being an offtaker of last resort for any surplus renewable energy.

[39] *Based on average household consumption in Queensland, New South Wales, Victoria, and South Australia in 2021, from AEMC, Residential electricity price trends 2021: final report, AEMC, 2022, p. 26, Table 4.1, accessed 28 September 2022.*
[40] *This value is based on 12 kWh per kg of silicon per CRU, Silicon and Polysilicon Report, p. 62, and PwC market research.*

Horizon 1 – Ensure risk is shared between solar developers and operators

Wholesale demand response

The wholesale demand response (WDR) mechanism was instigated on the NEM in October 2021 and enables large energy consumers to effectively participate in wholesale energy markets.

The mechanism allows energy consumers to alter their demand for power in response to price signals from the wholesale energy market. A participant can "sell" its unused demand in response to the market (i.e. ability to fluctuate load) and can receive compensation for the unused power. The mechanism can help relieve the load on the NEM and assists the market operator in its management of the NEM.

The WDR mechanism presents an opportunity for a load centre with the ability to fluctuate its load – such as a silicon smelter – to potentially reduce its energy costs and allow it to respond to the availability of renewable power in the market.

In the case of a PPA, WDR could be a feature of the contract. Including terms for the energy user to reduce its energy use at certain times benefits the energy producer by allowing them to redirect this unused energy to the spot market to take advantage of spot prices when they are highest. This benefit is shared with the energy user through a lower overall PPA price. For a silicon smelter, the WDR mechanism presents an opportunity for reductions in energy costs.[41] However, there are limits to which this can be employed given the toll on the smelting process that ongoing furnace shutdowns would eventually have.

Energy recovery in silicon smelting process

Energy recovery in the silicon smelting process can be integrated into silicon production plants. This is a unique opportunity with silicon smelting, as only 40% of the energy input into the furnace is from electrical energy, with the remainder of energy derived from the exothermic combustion of the reductants. Recovered thermal energy can be recycled back into the smelting furnace. Recovered energy can comprise 30% to 40% of energy requirements in the smelting process, significantly reducing energy costs and the carbon footprint.

Elkem, a Norwegian smelter with a total silicon capacity of 170 ktpa[42] currently recovers 900 GWh of energy per year – approximately 30% of its electrical energy requirements.[43] For context, 900 GWh is more than half of the production capacity of Cooper's Gap Wind Farm, Australia's largest wind project.[44]

Action 3: Ensure that solar project developers and operators share the development risks and benefits

All stakeholders have a role to play in reducing the risk involved in the development of new projects in the silicon and solar cell supply chain. Australian solar developers, who will benefit from a diversified and more secure supply chain, should be strongly encouraged to share in the development and financing risk of silicon projects.

Australian solar project developers can encourage new Australian quartz and silicon projects by committing to, or preferencing, the purchase of panels and modules that have been manufactured with Australian-sourced quartz and silicon. Developers can build partnerships with overseas cell and panel manufacturers that have links to Australian silicon, building on the concept of 'friend-shoring'[45] and ensuring that upstream Australian products can find buyers in the global silicon and solar cell supply chain. The willingness of large-scale Australian developers to engage as parties in end-to-end supply chain agreements is critical to enabling sustainable quartz and silicon production in Australia.

End users in the silicon and solar cell supply chain can help mitigate fundraising risk by contributing to pre-production capital expenditure, benefiting both silicon developers and solar cell end users. This scenario is akin to an electric vehicle car manufacturer taking a financial stake in a battery metal mining project, which is emerging as a procurement strategy in that industry.

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41 UTS Institute for Sustainable Futures, Best of Both Worlds - Renewable Energy and Load Flexibility for Australian Business Customer, UTS Institute for Sustainable Futures, 2018, accessed 5 October 2022.
42 CRU, Silicon and Polysilicon Report, Table 50.
43 Elkem, New energy recovery plant at Elkem Salten, Elkem, accessed 20 September 2022.
44 AGL, Coopers Gap Windfarm, AGL, accessed September 2022.
45 A term popularised by US Treasury Secretary Janet Yellen in a special address on the on the future of the global economy and US economic leadership to the Atlantic Council, 13 April 2022.
46 CRU, Silicon and Polysilicon Report, p. 138.
47 Ibid, p. 114.

Horizon 1 – Establish test facilities, develop ‘local content’ incentives and connect with partners

Action 4: Fund and establish test facilities to support the silicon industry

A prospective silicon and solar cell supply chain in Australia, consisting of quartz extraction and silicon smelting, requires several testing facilities:

1. reductant testing: reductants require testing for reactivity, determining suitability for use in the smelting process[48]
2. quartz testing: samples of quartz must be analysed for chemical purity and tested in smelting conditions to evaluate performance
3. silicon testing: facilities able to test silicon to determine suitability for different markets and buyers.

Quartz testing as feedstock for silicon and silicon testing as an input for polysilicon is highly standardised and the required equipment is available internationally.

Reductant testing is more complex. Currently, the global industry relies on a technology to test reductant reactivity that is owned by the Norwegian science agency, SINTEF. The ASAP recommends that Australia develop its own capability and technology in reductant testing to reduce reliance on offshore R&D and licensing.

There is an immediate requirement for Australia to develop its own testing technology and capability.

Government could provide support for reductant testing through:

- supporting the R&D undertaking required to develop an alternative, proprietary reductant reactivity test
- provide funding for (or grant funding to develop) a national test facility for reductants. A single test facility should be sufficient to support the Australian industry. The construction costs to build a local test facility would be insignificant in the context of establishing the silicon production industry.

Action 5: Phase in ‘local content’ incentives for new solar project developments

Government encouraging local content in new solar project developments would help to stimulate and support the development of Australia’s silicon industry and incentivise involvement of solar project developers in the supply chain.

Local content requirements (LCRs) can be introduced as part of eligibility requirements in renewable energy public tenders. A recent example is in the Victorian Renewable Energy Target auctions. LCRs can also be designed as thresholds for manufacturing for projects or businesses to receive grants, tax credits or other benefits. For example, the Inflation Reduction Act in the US has outlined tax credits for manufacturers of vehicles with final assembly in North America. A similar incentive could be introduced for Australian solar projects using panels that have a component of Australian-sourced silicon.

Action 6: Adopt a ‘market–maker’ role with international partners

Progress to silicon and solar cell supply chain integration will be incremental, and Australia will remain reliant on overseas countries and international companies that are responsible for, or operate, other parts of the supply chain for some time. This creates an opportunity to strengthen strategic relationships and actively develop the concept of ‘friend-shoring’.

Trade-focused government agencies could adopt a market–maker role by connecting Australian silicon producers to overseas polysilicon producers and solar cell manufacturers and linking that supply chain to Australian solar project developers.

Australia has recently progressed plans for multilateral coordination with the US, Japan, and India – the member nations of the Quadrilateral Security Dialogue (the Quad). Among other initiatives, the Quad will work to secure critical mineral supply chains that are essential to clean energy technologies.

[48] This refers to the ability of the reductant to react efficiently with the intermediate silicon compounds during the smelting process – this is critical and directly impacts silicon recovery rates and plant efficiency.

Horizon 1 – Provide targeted funding support and invest in domestic R&D

Case study: India

In addition to the Quad, of which both India and Australia are parties, there are growing ties between the nations with respect to critical minerals and clean energy supply chains.

The Australia–India Economy Cooperation and Trade Agreement was initiated in July 2021 to promote growth in Australian mineral exports to India and support Indian investment in critical minerals projects. The key message is that mutual benefit is recognised between India and Australia with respect to critical minerals and supply chains.

'India is reaching out and saying we want to be an alternative tech hub to China.' Lisa Singh, Chair, Australia India Institute[49]

India is pursuing a solar cell and solar PV supply chain diversification strategy.[50, 51] The second round of its Production-Linked Incentive (PLI) scheme solar plan was signed in September 2022 and includes INR195bn/US$2.4bn to establish 65 GW of fully and partially integrated solar PV manufacturing capability.[52] India currently has 15 GW of solar production capacity in module assembly and some cell manufacturing capability - the country is aiming to work 'backwards' up the supply chain into polysilicon production.[53, 54]

Solar cell supply chain companies in Australia and India can work together to establish an integrated supply chain between the countries, particularly on the prospect of exporting Australian silicon to India.

Action 7: De-risk new supply chain development through targeted funding support

Governments can take a more direct role in reducing the risk in developing a domestic silicon production industry through targeted action. Federal and state government funds can directly allocate capital to projects or supporting infrastructure to enable projects. Governments can also play a role through advocacy on behalf of the industry opportunity to domestic and international sources of capital – indicating to investors government priorities in critical mineral industries and seeking energy independence. The recently announced National Reconstruction Fund, through its Value-Adding in Resources Fund, could be applied to develop Australia's silicon production industry.

Action 8: Develop alternative reductants for silicon smelting and investigate next-generation processes and technologies

Developing alternatives to coal for carbon reductants in silicon smelting is integral to Australia's silicon industry and important for decarbonising the supply chain. The main reductant used by silicon producers – low-ash coal from Colombia, which is processed (washed) in Europe – is not a viable long-term option for Australia given its availability, deteriorating quality and escalating price.

A new, local and sustainable source of charcoal and biochar is required.

Sourcing charcoal

Purpose-built charcoal and biochar plantations could be considered in the development plans for a new silicon smelter. New and innovative sources of charcoal should be considered, such as aligning charcoal sourcing with efforts to control invasive species such as prickly pear and acacia. Investigations are underway on the use of acacia as an input for biomass in Queensland.[55]

As an example, connecting companies that clear prickly pear or invasive acacia species with charcoal producers could provide mutually beneficial outcomes.

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[49] Connors E, 'Battle of the billionaires: the rush to green hydrogen,' Australian Financial Review, 2022, accessed 28 September 2022.
[50] PM India, Cabinet approves Production Linked Incentive Scheme on 'National programme on High Efficiency Solar PV Modules' for achieving manufacturing capacity of Giga Watt (GW) scale in High Efficiency Solar PV Modules, PM India, 2022, accessed 4 October 2022.
[51] CRU International Ltd (CRU), Silicon and Polysilicon Report, CRU, 2022, p. 9.
[52] Gupta U, 'Indian government approves second phase of solar manufacturing incentive scheme', PV Magazine, 2022, accessed 8 October 2022.
[53] CRU, Silicon and Polysilicon Report, p. 26.
[54] Gupta U, 'Making India a manufacturing hub for solar-based, decentralized energy products', PV Magazine, 2022, accessed 9 October 2022.
[55] Peacock B, 'Queensland company promises to turn noxious weeds into "green coal"', PV Magazine, 2022, accessed 5 October 2022.

Horizon 1 – Collaborate with international R&D experts

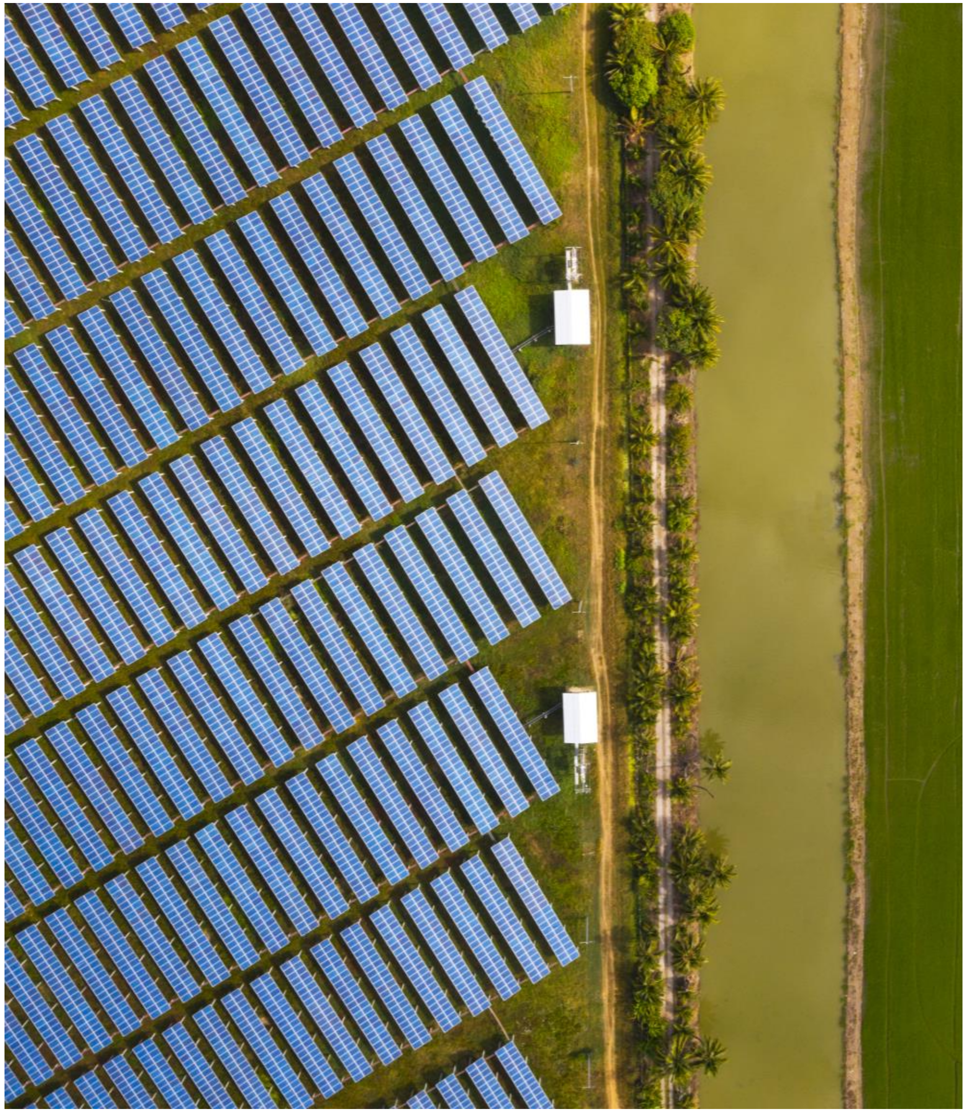
'Designer' charcoal is a current area of research that evaluates charcoal production for specific industrial applications. Purpose-built charcoal plantations could be designed that use low-cost and sustainable sources to supply charcoal for the silicon smelting process, having advantages over existing charcoal production technologies.

Action 9: Participate in related international R&D initiatives

There are prospective silicon industry R&D projects being progressed globally. The most potentially transformative advance is the metallothermic reduction process, which converts quartz into silicon without the use of carbon.
The potential benefits include:

- the direct processing of high-quality quartz into solar cell quality, bypassing the traditional polysilicon step in the supply chain
- reductions in carbon dioxide emissions, as a carbon reductant is not required
- reductions in heat and energy requirements
- the possible viability of silica sands in the process, with the potential to unlock a new and abundant category of feedstock.

Metallothermic reduction technology is not currently commercial and is unlikely until Horizon 3. However, the Australian scientific industry can begin collaborating with global counterparts (e.g. SINTEF in Norway) to advance the technology now.



Horizon 2 – Address the concentration risk in the global supply chain

Action 1: Develop ingot, wafer and solar cell manufacturing capabilities

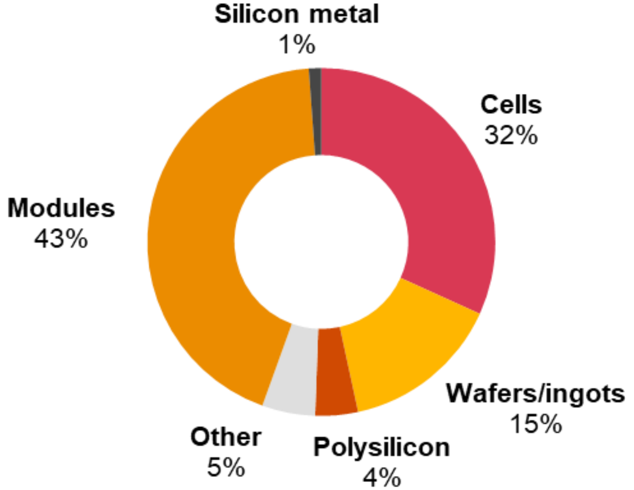
The higher-technology supply chain steps of manufacturing ingots, wafers and modules are the most geographically concentrated. To reduce risks that might arise from this current highly concentrated supply chain segment, Australia must find new partners or build this capability locally. Local production is the objective of Horizon 2.

Polysilicon production is more geographically diverse than other steps in the supply chain. In 2021, China accounted for less than 75% of global capacity.[56] Australia has the potential to partner with a range of polysilicon suppliers while it addresses the actions in Horizon 2.

Ingot, wafer and cell manufacturing is a labour-intensive process (Figure 17) and developing capacity in Australia would create job opportunities. Approximately 600 jobs are required for every gigawatt of ingot, wafer and cell manufacturing capacity.[57]

Furthermore, ingot, wafer and cell manufacturing facilities are expected to require less upfront capex to construct than a polysilicon facility of similar capacity.[58,59]

Figure 17: Solar supply chain employment concentration



Sources: IEA, Special report on solar PV global supply chains, p. 95; CRU, Silicon and Polysilicon Report, p. 106; PwC analysis from publicly available information.

Action 2: Invest in module manufacturing and recycling initiatives

Module manufacturing

Australia has proven capability in domestic solar PV module manufacturing and assembly. Australia's commitment to the development of more solar projects requires approximately 2 million panels per GW of capacity.[60] This scale creates an opportunity to increase domestic modulate manufacturing capabilities.

Module manufacturing

Reliable solar cell supply is critical for module production. Solar cells are constantly being modified and improved, often by varying the cell wafer size. Changes to the wafer size affects the module manufacturing and assembly processes. Manufacturing facilities must be updated to accommodate the larger cells. This creates risk for module manufacturers.

Australian module manufacturers will remain reliant on the production and design decisions of other territories until a domestic cell industry develops. Australian cell manufacturing capacity will allow module manufacturers to make longer-term investment decisions, including around expansion, scale up and automation.

Module recycling and the circular economy

Establishing a genuinely circular solar PV supply chain will require a commitment from all supply chain participants. Australia should look to unlock economies of scale to develop the panel recycling industry.

A uniform government policy is needed that clearly allocates responsibility for panel recovery and recycling, beginning with the categorisation of solar waste. Solar waste should be categorised as hazardous and banned from landfill, thereby creating a new waste stream specific to solar panels. Currently, only Victoria considers solar panels as hazardous waste.[61] National adoption of this policy could alter the comparative cost of panel recycling and encourage development in the end-of-life industry.

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[56] IEA, *Special report on solar PV global supply chains*, p. 44.
[57] Ibid., pp. 94–95.
[58] Ibid., p. 122.
[59] Assuming 3 t of polysilicon per GW of solar capacity, per Figure 4.
[60] PwC analysis, assuming 550W modules are employed.

Horizon 2 – Develop manufacturing and recycling capabilities and continue R&D investment

Regulatory frameworks should include recycling targets, clearly defined responsibilities of all stakeholders and accreditation of recycling companies.

The logistics and costs of transporting expired panels to recycling facilities must be examined. Proximity to solar end-use sites (e.g. industrial scale solar arrays) will be essential.

Case study: European Union

The European Union was the first jurisdiction to establish a solar PV-specific recycling policy.[62] The 2012 Waste Electrical and Electronic Equipment Directive established minimum requirements and targets for solar panel recycling and required 80% of the materials used in panels to be recycled.

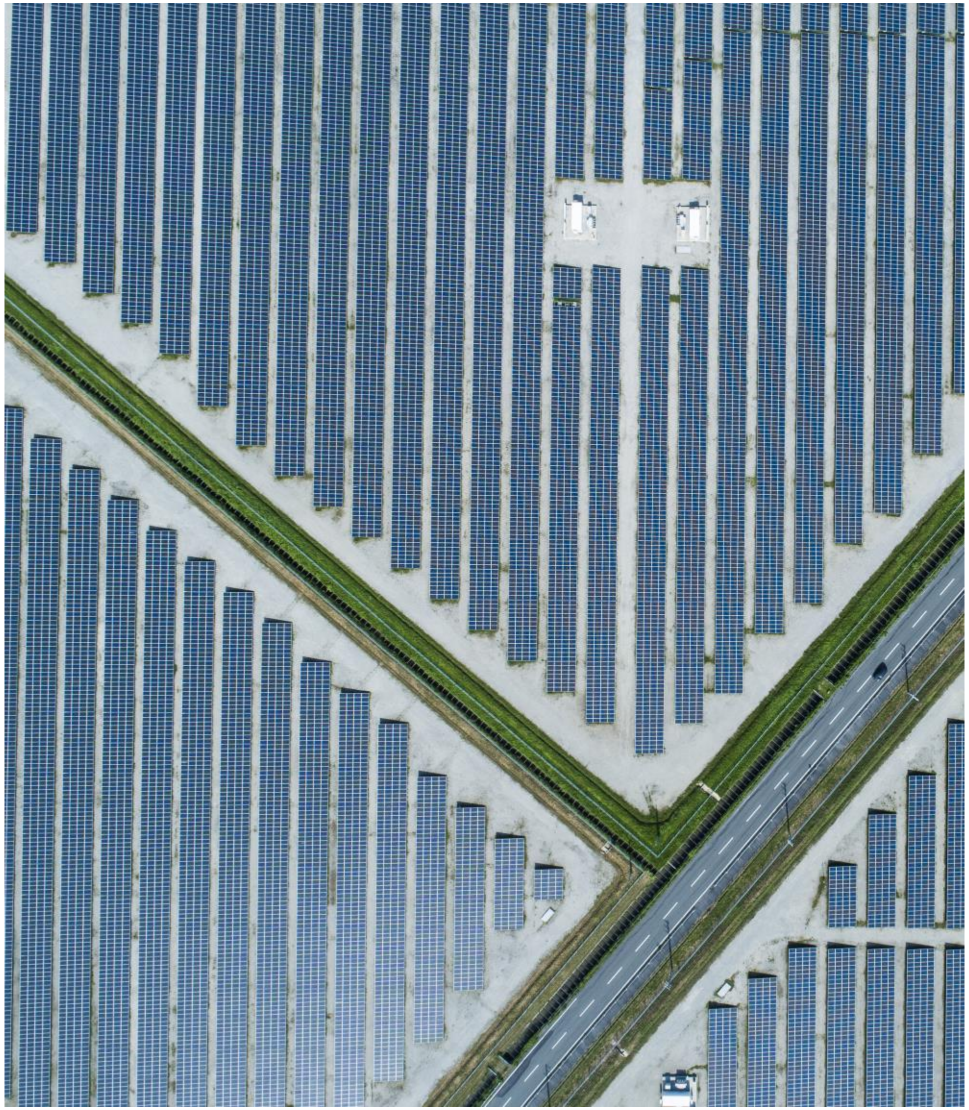
Action 3: Explore and assess emerging technologies

Hydrogen

Hydrogen has the potential to be used as a replacement reductant for carbon in the silicon smelting process and it is already being evaluated for use in Australia's steel and aluminium industries. 'Low emissions metals' production is a priority area for the Australian Renewable Energy Agency (ARENA),[63] which is providing funding to projects and companies.

Actions that the Australian R&D community could undertake include:

- leveraging existing and ongoing hydrogen economy research into carbon reductant alternatives
- collaborating with international research organisations that have aligned research capabilities and ambitions
- seeking additional industry and government support to accelerate this research.



[61] Mathur D et al., 'Do solar energy systems have a mid-life crisis? Valorising renewables and ignoring waste in regional towns in Australia's Northern Territory', ScienceDirect, p. 2, accessed 4 October 2022.
[62] PwC research.
[63] ARENA, Strategic priorities, ARENA, 2022, accessed 5 October 2022.

Horizon 3 – Complete integrated supply chain

Action 1: Develop polysilicon manufacturing capabilities

In Horizon 3, supply chain integration is completed by developing polysilicon production capacity. This is a Horizon 3 undertaking due to:

- Technical complexity – polysilicon production involves many stages of complex chemical reactions. Optimal technical processes, which are protected by trade secrets and patents, represent barriers to entry
- Capex requirements – building polysilicon capacity is the most expensive stage of the solar PV supply chain. CRU estimates the cost to build a new polysilicon plant (60ktpa capacity) would cost approximately US$3.9bn[64]
- Geographic diversity in polysilicon production – polysilicon production is geographically more dispersed than other production steps in the supply chain. This provides scope for Australian to partner with offshore jurisdictions, such as Germany and the US.

Action 2: Focus R&D efforts on developing and scaling up emerging and future technologies

R&D investment and fostering innovation is fundamental to each step in the Australian Silicon Action Plan. It is important that Australia's research and science institutions remain funded, motivated, and active in silicon and solar cell research given the importance of the industry in the energy transition.

[64] *CRU, Silicon and Polysilicon Report, p. 122.*

Putting ASAP into action

All stakeholders in the silicon and solar cell ecosystem have a role to plan in implementing the ASAP – government and policymakers, quartz and silicon project proponents, financiers, R&D participants and local communities.

Horizon 1: Silicon production

Incentivise the supply of raw materials and build silicon production capacity in Australia

Action 1: Establish an industry standard for quartz quality for use in the solar cell supply chain

Action 2: Integrate renewable energy generation and energy recovery into the silicon production process

Action 3: Ensure that solar project developers and operators share the development risks and benefits

Catalyse initial growth

Action 4: Fund and establish test facilities to support the silicon industry

Action 5: Phase in 'local content' incentives for new solar project developments

Action 6: Adopt a 'market–maker' role with international partners

Action 7: De-risk new supply chain development through targeted funding support

Investigate next-generation processes and technologies

Action 8: Develop alternative reductants for silicon smelting and investigate next-generation processes and technologies

Action 9: Participate in related international R&D initiatives

Horizon 2: Solar cell manufacturing

Expand Australia's supply chain position

Action 1: Develop ingot, wafer and solar cell manufacturing capabilities

Action 2: Invest in module manufacturing and recycling initiatives

Action 3: Explore and assess emerging technologies

Horizon 3: Integrated supply chain

Complete integration of low carbon and circular solar cell supply chain

Action 1: Develop polysilicon manufacturing capabilities

Action 2: Focus R&D efforts on developing and scaling up emerging and future technologies

ASAP with ASAP

We must move as soon as possible to implement the Australian Silicon Action Plan.

Renewables, including solar power, will be the biggest contributor to the global power mix by 2050. Rapid and large-scale instalment of new solar projects will have a major impact on the success of Australia's (and the world's) energy transition.

An anticipated 360 GW of installed solar in Australia is needed by 2050 to achieve our vision of being a clean energy and green hydrogen superpower. Our current reliance on a concentrated silicon and solar cell supply chain poses risks to Australia's energy independence and our ability to achieve the national emissions targets enshrined in the Climate Change Act.

By implementing the Australian Silicon Action Plan, Australia also stands to benefit from:

Employment and reskilling/ redeployment opportunities

Improved energy security and independence

Economic benefit from adding value to Australia's mineral endowment

Development of new industries with high ESG operating standards

This vision will not be achieved without clearing significant hurdles.

The ASAP sets out actions designed to orientate Australia towards the development of an integrated silicon and solar cell supply chain. This will require a high level of collaboration between all stakeholders in the solar cell ecosystem, including quartz and silicon producers, governments at state and federal level, R&D providers and solar developers in this country.

We don't have time to waste.

Glossary

Abbreviation	Term
A$	Australian dollar
AEMO	Australia Energy Market Operator
ARENA	Australian Renewable Energy Agency
ASAP	Australian Silicon Action Plan
CEC	Clean Energy Council
CRU	CRU International Ltd
CSIRO	Commonwealth Scientific and Industrial Research Organisation
ESG	Environmental, social and governance
GW	Gigawatt
GWh	Gigawatt hour
HPQ	High purity quartz
IEA	International Energy Agency
INR	Indian rupee
IRENA	International Renewable Energy Agency
ISP	Integrated System Plan
kt	Kilotonne
ktpa	Kilotonne per annum
kWh	Kilowatt hour
LCR	Local content requirement
Mt	Megatonne
MW	Megawatt
NEM	National Energy Market
PLI	Production linked incentive
Polysilicon	Crystalline polysilicon
PPA	Power purchase agreement
PV	Photovoltaic
PwC	PricewaterhouseCoopers
Quad	Quadrilateral Security Dialogue
R&D	Research and development
Reductant	Carbon sources used in carbothermic reduction reactions
t	Tonne
tpa	Tonne per annum
TW	Terawatt
US$	United States dollar
WDR	Wholesale demand response

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