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Silicon to Solar (S2S) Study Phase 1: Market Assessment Report

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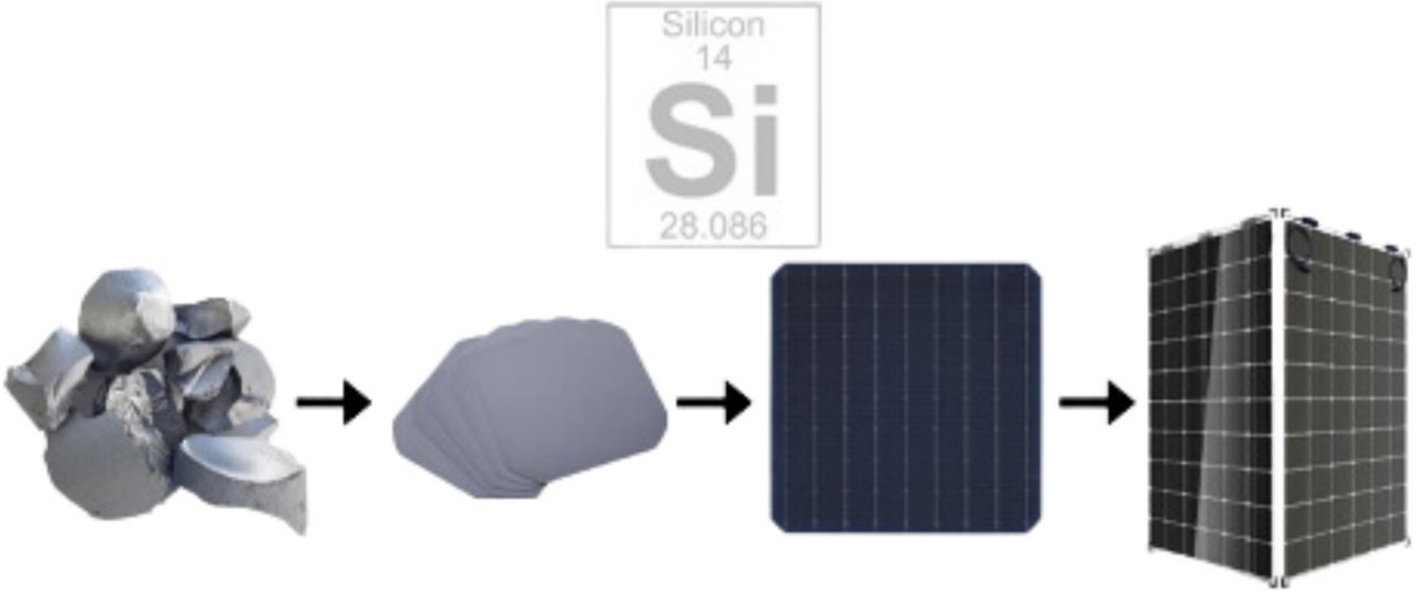

About the Australian Photovoltaics Institute (APVI)

The APVI is a not-for-profit, member-based organisation providing data analysis, reliable and objective information, and collaborative research to support the development and uptake of PV and related technologies. The APVI and its predecessors have been operating since 1993. APVI members are organisations and individuals from industry and academia with an interest in solar energy research, technology, manufacturing, systems, policies, programs and projects.

APVI undertakes deployment and information-focused projects and produces detailed technical and market publications, hosts seminars, workshops, conferences and member events, prepares submissions on key solar issues and promotes solar energy in the media. Examples include annual reports on PV uptake, targeted information on PV deployment, assessments of PV potential in various sectors, and development of high quality solar analysis tools via the SolarMap. The APVI organises the annual Asia-Pacific Solar Research Conference, a regional forum for communicating outcomes covering all aspects of solar-related research. In addition to Australian activities, the APVI provides the structure through which Australia participates in two IEA Implementing Agreements: PV Power Systems (PVPS) and Solar Heating and Cooling (SHC) and manages the international PVPS Secretariat. A range of international data is collated, analysed and reported on through these programs. Diversified manufacturing is a now a key topic under both these Programs.

The S2S project will assess whether parts of or the entire PV manufacturing value chain can be operational in Australia. For this project , the APVI will partner with the Australian Centre for Advanced Photovoltaics (ACAP), which is a key central agency to coordinate photovoltaic research activities in Australia.

Disclaimers

This report is Phase 1 of the “APVI Silicon to Solar Study”. The Study is conducted by the Australian PV Institute (APVI) under the Australian Renewable Energy Agency’s Advancing Renewables Program in collaboration with the Australian Centre for Advanced Photovoltaics, Bright Dimension, ITP Renewables and Deloitte.

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A large number of collaborating companies and government departments from Australia and overseas will provide input in Phase 2 and 3 of this Study through workshop sessions and will be listed in the final report of this Study. At this stage we would like to acknowledge the collaboration with the US Department of Energy, particularly, Dr. Paul Basore.

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EXECUTIVE SUMMARY

The target of net zero emissions by 2050 has now been accepted in Australia[1] and around the world. Achieving this target, requires a rapid transition to renewable energy. For Australia, with its abundance of sunshine and land, this means that solar power will provide most of the future electricity generation. Australia's potential as a renewable energy superpower is heavily reliant on the availability of solar modules for the generation of solar electricity, which are predominantly manufactured in China by companies owned by Chinese entities. This dependency on a single external source raises concerns about Australia's control or influence over the solar supply chain and, therefore, its renewable energy future.

Australia has three levers to manage and secure the continuous, reliable and cost-effective supply of solar power. Firstly, it can continue to depend on China as a single source; secondly, it can hope that the US, Europe or India, all of whom have stated ambitious manufacturing plans, will produce enough solar modules so that Australia can procure its share from these regions; thirdly, it can take some control over the solar photovoltaic (PV) supply chain by establishing local manufacturing capabilities. A successful supply chain strategy will entail setting and continuing to adjust all three levers over the coming decades to manage Australia's transition to renewable energy smoothly and successfully.

The Silicon to Solar Study (S2S Study) assesses the third lever of "taking some control back" in line with three guiding principles:

a) *Viable*: The manufacturing step in the value chain set up in Australia needs to be globally competitive and economically viable long term.
b) *Relevant:* The manufacturing facility needs to have a scale that is appropriate and relevant for future Australian and global PV demand.
c) *Timely*: The manufacturing capacity needs to be set up within a timeframe that is necessary to achieve net zero by 2050.

Using these guiding principles, the solar technology that forms the basis for the subsequent (Phase 2) techno-economic analysis and the required business and policy assessment has been narrowed down to be the silicon wafer based solar cell technology. The focus is on assessing if there is a credible future state in which Australia manufactures some or all of the steps of the Si-wafer based solar value chain, including:

- manufacturing highly purified poly-Si from metallurgical-grade silicon, using the standard Siemens chemical vapour deposition process,
- manufacturing monocrystalline ingots and wafers using Czochralski pulling and diamond wire sawing technology,
- processing solar cells using latest state-of-the-art mass-manufacturing cell technology (TOPCon/PERC), and
- assembling glass encapsulated solar modules.

A wide range of industry partners and collaborators has been engaged to ensure that the assessment is as relevant as possible and that the credible future state reflects the conditions under which a rational business would establish manufacturing in Australia.

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[1] Prime Minister of Australia, https://www.pm.gov.au/media/australia-legislates-emissions-reduction-targets, viewed 22 May 2023

INTRODUCTION TO PROJECT

THE ROLE OF PV IN MEETING NET ZERO TARGETS

A key driver for current and future solar photovoltaic (PV) deployment in Australia and around the world is heading towards net-zero carbon emissions by 2050. Australia's target is a 43% reduction in greenhouse gas emissions against 2005 levels by 2030 and net zero by 2050,[2] which is similar to the target for the European Union.[3] The respective US target is slightly more aggressive than that of Australia, with a 50 – 52% reduction by 2030.[4] China's short term target is even more aggressive at 65%, although the longer term target specifies that China will not reach net-zero until 2060.[5] To achieve net-zero globally, various reports suggest that somewhere in the vicinity of 15 TW – 60 TW of PV will need to be operating by 2050.[6,7] The lower value of 15 TW is roughly in line with the current total global electricity consumption of around 25,000 TWh pa,[8] which would require approximately 17 TW of solar. However, by 2050, with higher levels of electrification, global electricity demand is expected to almost double,[9] which would substantially increase the requirement for PV. Hence, higher levels of PV, in the range 30 – 60 TW, are likely, given that solar now provides some of the cheapest electricity in the world, with electricity bids from leading power plants heading towards AU$15/MWh.[10] The *Hydrogen Superpower* scenario reported by the Australian Energy Market Operator (AEMO) in the 2022 Integrated Systems Plan (ISP) suggests that Australia alone could require approximately 300 GW of PV by 2050.[11]

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[2] Australian Government, https://www.aofm.gov.au/sites/default/files/2022-11-28/Aust%20Govt%20CC%20Actions%20Update%20November%202022_1.pdf, viewed 15th May 2023.

[3] UNFCCC, https://unfccc.int/sites/default/files/NDC/2022-06/EU_NDC_Submission_December%202020.pdf, viewed 15th May 2023.

[4] The White House, https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/, viewed 15th May 2023.

[5] UNFCCC, https://unfccc.int/sites/default/files/NDC/2022-06/%E4%B8%AD%E5%9B%BD%E8%90%BD%E5%AE%9E%E5%9B%BD%E5%AE%B6%E8%87%AA%E4%B8%BB%E8%B4%A1%E7%8C%AE%E6%88%90%E6%95%88%E5%92%8C%E6%96%B0%E7%9B%AE%E6%A0%87%E6%96%B0%E4%B8%BE%E6%8E%AA.pdf, viewed 15th May 2023.

[6] International Energy Agency, 2021 "World Energy Outlook", https://www.iea.org/reports/world-energy-outlook-2021

[7] VDMA, "International Technology Roadmap for Photovoltaic (ITRPV) – 2021 Results", Mar. 2022.

[8] Statistica, https://www.statista.com/statistics/280704/world-power-consumption/, viewed 12th May 2023.

[9] Energy Live News, https://www.energylivenews.com/2021/01/18/global-power-consumption-to-almost-double-by-2050/#:~:text=Global%20power%20consumption%20will%20almost,30%25%20by%20mid%2Dcentury, viewed 15th May 2023.

[10] Renew Economy, https://reneweconomy.com.au/solar-heads-to-1ckwh-before-2020-after-mexico-sets-record-low-62163/, viewed 23rd April, 2023.

[11] Australian Energy Market Operator, "2022 Integrated Systems Plan", page 40. Published December 2021.

PROJECT MOTIVATION: DIVERSIFYING PV SUPPLY CHAINS AND SECURING PV MODULE SUPPLY FOR AUSTRALIA

Australia's exit from carbon intensive electricity generation is well on its way, as demonstrated on 28th April 2023 when the last coal-fired power generation unit at AGL's Liddell Power Station was switched off.[12] The decommissioned generation capacity will be replaced with solar, wind and hydro power, combined with battery and hydrogen storage to ensure the necessary firming capacity. However, Australia's ambitions go beyond replacing the existing fossil-fuel power generation with renewable energy. According to recent announcements, the Parliament of Australia is "focusing on identifying challenges and opportunities for Australia to capitalise on our abundant natural resources to drive economic growth, create new industries and jobs and become a green energy superpower".[13] In the future state of a green energy superpower, Australia will export renewable energy directly via cable, indirectly via hydrogen or other forms of energy storage and also embodied within low carbon products manufactured in Australia. It will manufacture green steel, green aluminium, green ammonia and other goods utilising abundant renewable energy. In addition, increased electrification of general manufacturing processes as well as domestic appliances like water heating, cooking and charging of electric vehicles will increase Australia's electricity demand. In AEMO's ISP published in 2022, the Hydrogen Superpower Scenario will require a 34-fold increase of the current capacity of Variable Renewable Energy (VRE) with the majority coming from solar power[14]. Even in AEMO's less ambitious "Step Change Scenario", the majority of power generation capacity in the National Electricity Market (NEM) will rely on solar power from distributed and utility-scale solar generators. This means, no matter which scenario unfolds, Australia will require a steady, reliable and affordable supply of solar modules to power its renewable energy future.

In 2022, 3.9GW[15] of solar power generation was installed in Australia. Almost all solar modules installed in 2022 were imported from overseas, with less than 30 MW assembled in Adelaide by Tindo Solar from imported solar cells.[16]

There are 5 distinctive steps in the manufacturing process of solar modules (Figure 1), of which the ingot and wafer steps are usually treated together. The details of these manufacturing steps will be discussed in more detail later in this report.

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[12] Energy Magazine, https://www.energymagazine.com.au/liddell-power-station-shut-down-after-52-years-of-operation/, viewed 28th April, 2023.

[13] Parliament of Australia, 18th Oct 2022, https://www.aph.gov.au/About_Parliament/House_of_Representatives/About_the_House_News/Media_Releases/Australias_transition_to_a_green_energy_superpower, viewed 12th May 2023
Parliament of Australia, 18th Oct 2022, https://www.aph.gov.au/About_Parliament/House_of_Representatives/About_the_House_News/Media_Releases/Australias_transition_to_a_green_energy_superpower
LINK "https://www.aph.gov.au/About_Parliament/House_of_Representatives/About_the_House_News/Media_Releases/Australias_transition_to_a_green_energy_superpower"https://www.aph.gov.au/About_Parliament/House_of_Representatives/About_the_House_News/Media_Releases/Australias_transition_to_a_green_energy_superpower, viewed 12th May 202

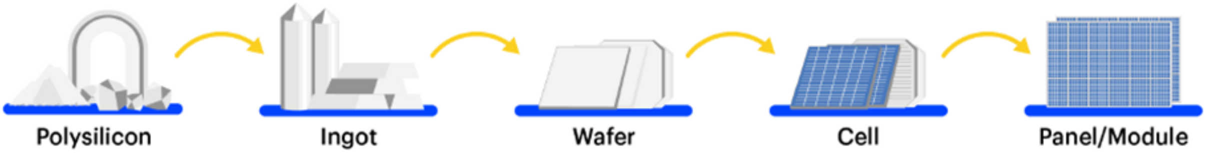

Figure 1: Main manufacturing steps across the PV value chain.
Source: IEA "Special Report on Solar PV Global Supply Chain", (Dec. 2022)

Currently, the manufacturing value chain for solar modules is highly concentrated within China and Chinese owned companies (Figure 2).

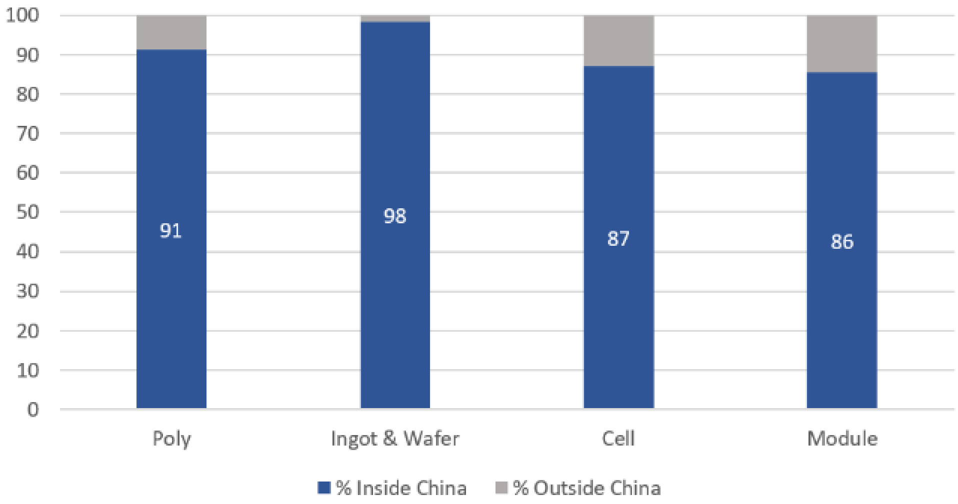

Figure 2: Percentage of global PV manufacturing production inside and outside of China in 2023. Note that some of the production activities outside China in this figure include Chinese owned operations. Source: 2023 PV Cell Tech[17].

The extremely high concentration represents a risk for Australia's decarbonisation plans and its ambition of becoming a renewable energy superpower. Electricity is fundamental to Australia's economy, and its future state of electricity generation from renewable energy is almost entirely dependent on product supply from China.

Australia has three levers to manage this risk of concentration in the supply chain:

i. **Depend on China:** Australia can continue depending on China, who as a nation has supplied the world with affordable, high-quality solar cells for the last decade. The underlying assumption would be that an uninterrupted, rapidly growing supply of solar modules can be maintained for the next couple of decades whilst Australia transitions to and maintains a renewable future and while Chinese and global demand also increases steeply.
ii. **Others solve the issue**: Australia can hope to diversify the supply of solar modules from other regions, like the US, Europe, India and others. Many countries have recognised the critical situation in the solar supply chain and have acted by developing initiatives to set-up a local supply chain, most notably in the US through the Inflation Reduction Act (IRA).
iii. **Take some control back**: Australia could build up manufacturing capacity across parts of or the entirety of the solar value chain and actively participate in a diversified global solar supply chain.

Each of these levers carries its own risks and benefits, however, they are not mutually exclusive, and a combination of all three can provide risk mitigation and synergies of benefits.

Lever 1 - Depend on China: China is currently, and predicted to remain in the future, the largest manufacturer and user of solar modules[18]. There are numerous reasons why a continuous dependence on only China as a supplier carries high risk, such as supply disruption due to natural disasters, internal energy market issues, pandemics and geopolitical tensions. Some of these are being addressed by Chinese companies through operating manufacturing facilities in different countries. However, China itself has very ambitious decarbonisation targets, and Australia's demand for about 5 GW p.a. of solar modules, compared to global production of about 1,000 GW p.a. in the near future, means that Australia has very little bargaining power in the global competition for economically priced solar modules. Whilst Australia will continue to purchase solar modules from China in the foreseeable future, any disruption in this set-up of the supply[19] would mean a direct impact on Australia's transition to renewable energy.

Lever 2 - Others solve the issue: If Australia is uneasy about completely relying on steady and reliable supply from China, it could hope that manufacturing initiatives in other regions will result in excess solar module supply which can be procured in Australia at competitive prices and acceptable quality. The US has passed the Inflation Reduction Act (IRA), which contains US$ 369 billion for climate change mitigation[20]. The IRA contains direct solar manufacturing tax credits with targeted support for solar-grade poly-Si, wafer, cell and module manufacturing. The IRA will be analysed in more detail in the policy section in Phase 2 of this study. Similarly, the European Commission announced in March 2023 the "Net-Zero Industry Act: Making the EU the home of clean technologies manufacturing and green jobs"[21] as a part of the Green Deal Industrial Plan[22]. With the Act, the EU wants to create PV manufacturing capacity to supply at least 40% of EU's needs in 2030. Germany alone wants to add an additional 150 GW of solar

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[18] PV Cell Tech, "PV Manufacturing & Technology Quarterly Report", April 2023.

[19] Note that during the Covid pandemic, module supply to Australia was severely impacted. Between the end of 2020 and the end of 2021 global module shipping costs alone rose to over 50%, (https://colitetech.com/blog/why-is-the-cost-of-solar-increasing/).

[20] PV Tech, https://www.pv-tech.org/an-ira-deep-dive-how-significant-is-it-and-what-uncertainties-remain/ , 5th Jan 2023

[21] European Commission, https://ec.europa.eu/commission/presscorner/detail/en/IP_23_1665, viewed 4th May 2023.

[22] European Commission, https://ec.europa.eu/commission/presscorner/detail/en/ip_23_510 , viewed 4th May 2023.

by 2030[23]. India directly targets solar manufacturing through the Production-Linked Incentive (PLI) scheme. Applicants for the incentives need to submit single bids to set up individual manufacturing facilities with at least 1 GW of annual solar manufacturing capacity[24]. From an Australian perspective, these announcements might lead to new supply lines, however it still needs to be proven how quickly these capacities can be built[25] and whatever new manufacturing capacity is installed in these regions will still not meet the total local demand for solar power generation.

Recently, a promising avenue for collaborative growth has emerged through bilateral agreements between the US and India with Australia. Most tangible examples include the AUS-US Climate, Critical Minerals and Clean Energy Transformation Compact[26] and the Australia-India Green Hydrogen Taskforce[27]. These agreements aim to foster collaborative efforts and explore alternative supply chain options between nations, and will be considered in greater detail in Phase 2 of this study.

The current outlook, however, suggests that Chinese manufacturers will maintain their dominant position in the market[28], and it is unlikely that Australia's risk exposure will experience significant improvement. Depending on other countries could subject Australia to ongoing supply chain risks, especially considering the existing supply chain issues in the PV industry. Additionally, establishing production capacities in alternative countries is expected to take longer than in China, further exacerbating the potential risks.

Lever 3 – Take some control back: Australia used to have moderate solar cell manufacturing capability until 2012[29] and has a globally recognised track record in solar technology development. The PERC[30] cell technology used in most commercial solar modules today and the increasingly popular TOPCon[31] technology are both based on inventions made at the University of New South Wales, Sydney[32]. Australian researchers have spear-headed the development of the PERC technology over decades, as well as a number of solar cell technologies utilising copper plating, and key processes, such as advanced hydrogen passivation, for all silicon solar cell technologies. If solar manufacturing across the solar value chain is set up in Australia, it would mitigate the supply risk and increase Australia's resilience to manage the transition to a renewable energy future. However, any initiatives leading to onshore manufacturing will need to be seen in the context of the overall declining capability of manufacturing in Australia. Australia's ranking according to the Economic Complexity Index[33] has fallen from 60 in 2000 to 91 in 2020[34]. Australia is currently ranked between Kenya and Namibia. If Australia wants to take control back over the

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[23] Renew Econmy, https://reneweconomy.com.au/germany-unveils-plans-to-add-150gw-of-solar-by-2030-as-gas-use-slumps/#:~:text=Total%20capacity%20is%20planned%20to,reach%20more%20than%2010%20GW, viewed 12th May 2023

[24] PV Magazine, https://www.pv-magazine.com/2022/11/22/india-launches-second-phase-of-incentive-scheme-for-solar-manufacturing/ viewed 4th May 2023

[25] PV Tech, https://www.pv-tech.org/meeting-us-solar-needs-with-domestic-equipment-will-be-challenging-woodmac-details-iras-impact-on-manufacturers/, viewed 4th May 2023

[26] Prime Minister of Australia, https://www.pm.gov.au/media/australia-united-states-climate-critical-minerals-and-clean-energy-transformation-compact , viewed 29th May 2023.

[27] Prime Minister of Australia, https://www.pm.gov.au/media/opening-remarks-bilateral-meeting-prime-minister-india, viewed 29th May 2023.

[28] IEA, https://www.iea.org/reports/will-new-pv-manufacturing-policies-in-the-united-states-india-and-the-european-union-create-global-pv-supply-diversification, viewed 4th May 2023.

[29] Renew Economy, https://reneweconomy.com.au/silex-systems-closes-homebush-solar-pv-manufacturing-plant-93963/, viewed 4th May 2023.

[30] Passivated Emitter and Rear Cell (PERC)

[31] Tunnel Oxide Passivated Contact (TOPCon)

[32] Queen Elizabeth Prize for Engineering, https://qeprize.org/winners/martin-green, Viewed 29th May 2023.

[33] Atlas of Economic Complexity (University of Harvard) publishes a ranking of countries based on how diversified and complex their export basket is. Countries that are home to a great diversity of productive know-how, particularly complex specialized know-how, are able to produce a great diversity of sophisticated products.

[34] Harvard University, https://atlas.cid.harvard.edu/rankings, viewed 9th May 2023.

solar supply chain by stimulating local manufacturing, a broad initiative addressing the numerous shortfalls, such as the lack of equipment suppliers, skilled workforce, approval processes, support services, and many others that will need to be addressed in a coherent national effort.

Unless Australia focuses on securing the solar module supply chain, transitioning to renewable energy and becoming a renewable energy superpower carries a high level of risk. What's more, not transitioning to renewable energy is not an option for Australia, because Australia's economy and society would be left behind by other nations, who strive for a decarbonised world.

To successfully navigate this transition, all three levers of risk management will need to be set and adjusted carefully over the coming decades. If Australia goes full throttle on one lever but ignores the other two, the transition is likely to fail. Only a fruitful collaboration between Australia, China and the other regions that build out their solar manufacturing capacity can provide the speed and targeted approach necessary to transition to a world powered by renewable energy as quickly as necessary. Australia will need to find a way to manage a reliable, economical supply of quality solar modules by setting these three levers appropriately. While in this study all three levers of risk management are considered, it focuses its attention on the opportunities and challenges related to Lever 3 – 'Take some control back'. Considerations around the bilateral agreements previously mentioned and the viability of joint ventures between Australia and others (e.g., China, US, India, etc.) to set up manufacturing in Australia will also be discussed in more detail in Phase 2 of this study. Comparable studies are being conducted in other regions around the world[35], and have led to the development of the IRA in the US and the EU Green Deal in Europe.

This study aims to address the following questions:

- Is there a credible future state for PV manufacturing (across parts of or the complete value chain) in Australia that is economically viable and relevant in size as well as timeframe?
- What synergies exist with Australia's other industries and overseas trading partners that are also exploring PV manufacturing expansion which could help meet Australia's demand?
- What are the key barriers facing investors into the sector?
- What are the upstream and downstream benefits and drivers needed to support viable local PV manufacturing?
- What are the steps necessary to enable local solar manufacturing?

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[35] SEIA's American Solar and Storage Manufacturing Renaissance, https://www.seia.org/research-resources/american-solar-storage-manufacturing-renaissance-managing-transition-away-china ; VDMA's feasibility study on manufacturing https://www.pv-magazine.com/2023/03/28/germany-launches-feasibility-study-on-pv-manufacturing/; SolarPower Europe, https://www.solarpowereurope.org/press-releases/eight-actions-to-solar-power-eu-energy-independence-new-report .

PROJECT METHODOLOGY: VIABLE / RELEVANT / TIMELY

The S2S Study will assess how Lever 3 – 'Take some control back' can be set, so that Australia develops a credible future state in which potentially some or all steps in the solar value chain are manufactured on shore. Any initiatives taken in this regard will be set within the context of the other possible 2 levers: to secure solar module supply (Lever 1 – 'Depend on China' and Lever 2 – 'Others solve the issue').

This credible future state is assessed along three principles:

a) *Viable*: The manufacturing step in the value chain needs to be globally competitive and economically viable long term.
b) *Relevant*: The manufacturing facility needs to have a scale that is appropriate and relevant for future Australian and global PV demand.
c) *Timely*: The manufacturing capacity needs to be set up within a timeframe that is necessary to achieve net zero by 2050.

In parallel, S2S will assess any inherent competitive advantages unique to Australia, which provide additional values for onshore processing and ensure long-term sustainable competitiveness. To meet the timeliness criteria, the credible future state drafted by S2S will only rely on state-of-the-art manufacturing processes that have a Commercial Readiness Index (CRI) of 4 or higher[36].

S2S will not provide an exhaustive review of all *possible* onshore manufacturing scenarios but focus on one *credible* scenario to show the possibility and likelihood of this future state. This ensures that the credible future state can be achieved within a necessary timeframe and at a scale that is relevant without carrying undue commercial and / or technology risks. Nevertheless, once Australia has an established solar supply chain, new technologies will find it easier to enter the market as they will benefit greatly from the ecosystem developed through setting up large-scale solar manufacturing locally. Hence, technology choices proposed in this study will aim to provide a manufacturing baseline into which future new technologies can be integrated, when ready.

The S2S Study initially assesses the local and global forecasts of annual PV demand and manufacturing capacity out to 2050. This will help to establish the required growth trajectory and determine how much solar PV is needed, and by when. The result of this market analysis provides the guidance for the size of manufacturing that is to be assessed. The underlying technology will be based on the most likely, mass-manufactured silicon wafer based solar cell technology, to ensure that the three key assessment principles are being met. The main technology steps from poly-Si to module assembly will be described later in this report. Metallurgical silicon (mg-Si), the input material for poly-Si purification is not explicitly assessed in this report, because the supply chain is more diversified with over 30% from outside China. CSIRO published two reports in 2021[37] and 2022[38] with the focus mainly on the critical energy minerals related to renewable energy. In addition, Australia already has an onshore manufacturer of

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[36] ARENA, "Commercial Readiness Index for Renewable Energy Sectors", published Feb. 2014
[37] CSIRO, " Critical Energy Minerals Roadmap", published 2021.
[38] CSIRO, "Australian Silicon Action Plan", published 2022.

mg-Si, Simcoa in Western Australia, with a capacity of 52,000 t,[39] which is already more than Australia would require for its own solar demand.

Each step in the value chain from poly-Si to solar module is assessed in line with the Techno-Economic Analysis (TEA) framework and paired with business and policy analysis (Figure 3).

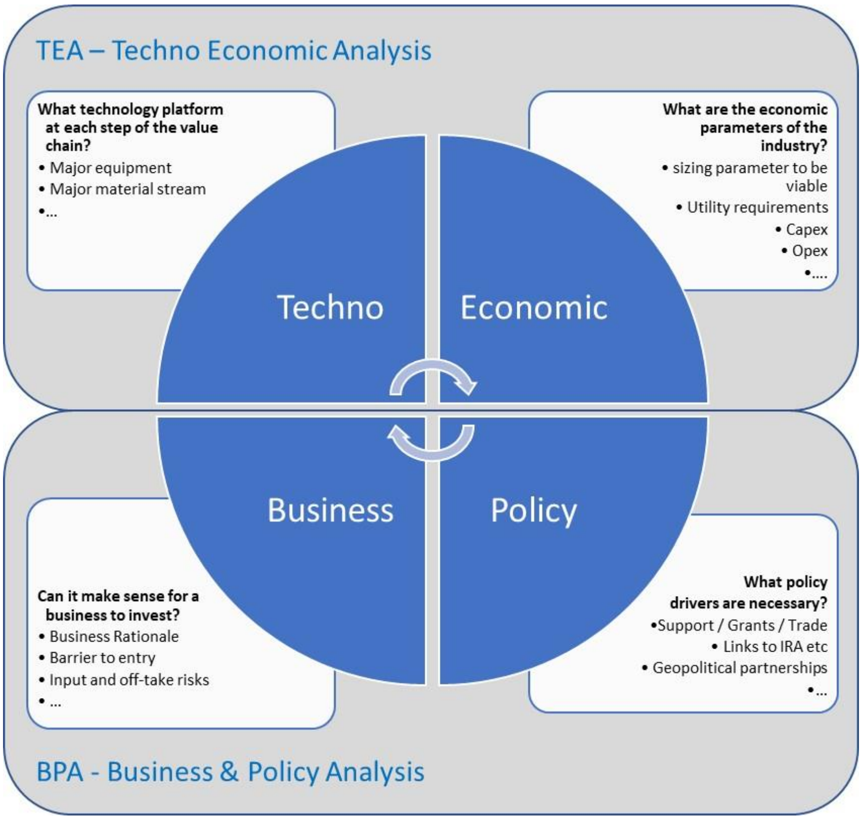

Figure 3: Techno-economic and business & policy framework

The TEA is carried out against 24 criteria including main technology, alternative technology, key players, IP consideration, input / output material flow, key equipment & suppliers, investment costs, operational costs, labour & skill requirements, logistics, environmental considerations, social licence, transfer of skills, and others[40]. The results of the TEA form the basis for the Business & Policy Analysis (BPA) which is guided by the key principles of *viability, relevance and timeliness.*

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[39] SIMCOA, https://www.simcoa.com.au/company, viewed 9th May 2023

[40] The framework of the 24 criteria for the TEA was developed by 12 solar technology experts from the S2S team and industry contributors.

PV MARKET PROJECTIONS 2030 & 2050

GLOBAL PROJECTIONS

Globally, the solar PV market is expected to continue growing rapidly, driven by declining costs, increasing demand for renewable energy, and supportive government policies. The International Energy Agency (IEA) in its Net Zero by 2050 scenario (WEO 2022) projects that total installed solar PV capacity could reach 4.8 TW by 2030 and 14.5 TW by 2050. However, in the past, IEA's WEO has consistently underestimated the growth of solar energy globally, as reduced costs and improvements in policy support have exceeded expectations. As of 2022, the total global installed PV capacity has grown by approximately 360 GW and is far higher than the IEA's expectations of a 190 GW increase[41]. Solar energy has become increasingly competitive with traditional fossil fuels, and technological advancements have made solar modules more efficient and affordable than most other renewable sources.

The anticipated proportion of solar PV in the energy markets for the years 2030 to 2050, varies with estimates ranging from 30% to 70% of the total power generation. Figure 4 illustrates instances of this, with BNEF's 2021 NEO Green Scenario and the ITRPV broad electrification scenario presented as the minimum and maximum estimates for the annual global demand for PV, respectively. In addition, Figure 4. shows the conservative scenario of global PV demand from the Chinese PV Industry Association (CPIA) and the forecast of module supply shipments reported in the quarterly PV Tech Research report.

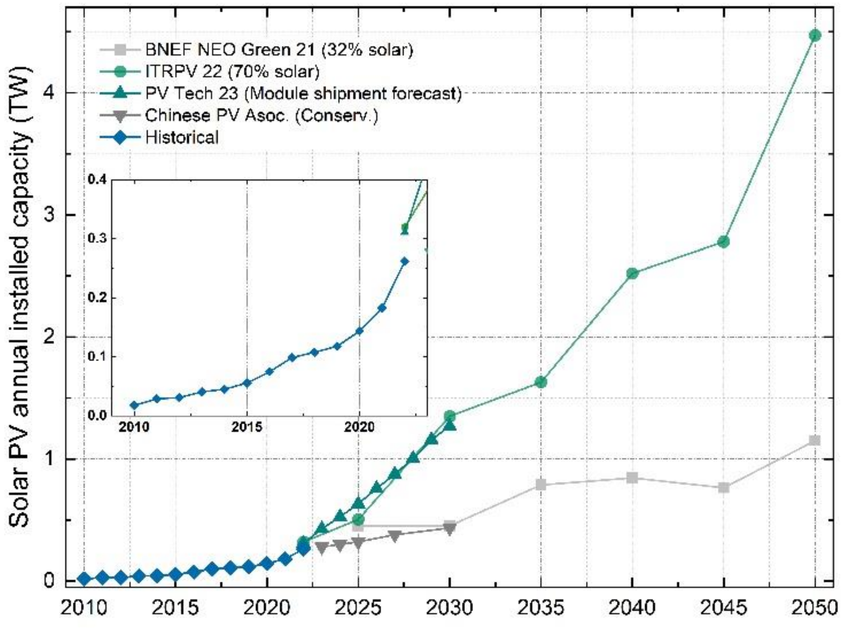

Figure 4: Global Solar PV annual demand forecast. Sources: PV Cell Tech[42], BNEF[43], ITRPV[44] and CPIA[45].

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[41] IEA, "Renewable Energy Market Update", May 2022.

[42] PV Cell Tech, "PV Manufacturing & Technology Quarterly Report", April 2023.

[43] BloombergNEF, "Solar PV Trade and Manufacturing: A Deep Dive", Feb. 2021.

[44] VDMA, "International Technology Roadmap for Photovoltaic (ITRPV) – 2021 Results", Mar. 2022.

[45] CPIA, "China PV Industry Development Roadmap", April 2023.

Considering historical trends and current projections, for the purpose of this work's analysis, it is anticipated that the annual global demand for solar PV will continue to increase and reach around 1 TW by 2030 and conservatively around 2 TW by 2050. If the ambitious electrification plan presented in the 2022 ITRPV report becomes a reality, which includes goals such as widespread adoption of clean energy, reduced energy consumption, accessible fresh water, and affordable power, the annual capacity additions could more than double by 2050, reaching around 4.5 TW per year (accumulating to over 63 TW of total installed capacity).

AUSTRALIAN RENEWABLE ENERGY TARGETS

In Australia, the government has set a target of achieving 82% of electricity from renewable sources by 2030,[46] resulting in a substantial expansion of the PV industry. As of the end of 2022, over 3 million Australian households have rooftop solar panels, and the total installed capacity has reached approximately 30 GW. AEMO predicts that in the next two decades, annual PV additions will range between 4 and 8 GW, according to their "step change" scenario – the most probable scenario as outlined in the 2022 AEMO ISP. This would lead to a total installed capacity of around 100 GW by 2050. Nonetheless, if Australia is to realise its ambition of becoming a hydrogen superpower, AEMO believes that the annual growth of PV capacity should double the current rate by 2025 and reach 15 GW per year by 2045, resulting in a cumulative capacity of approximately 300 GW by 2050 (See Figure 5).

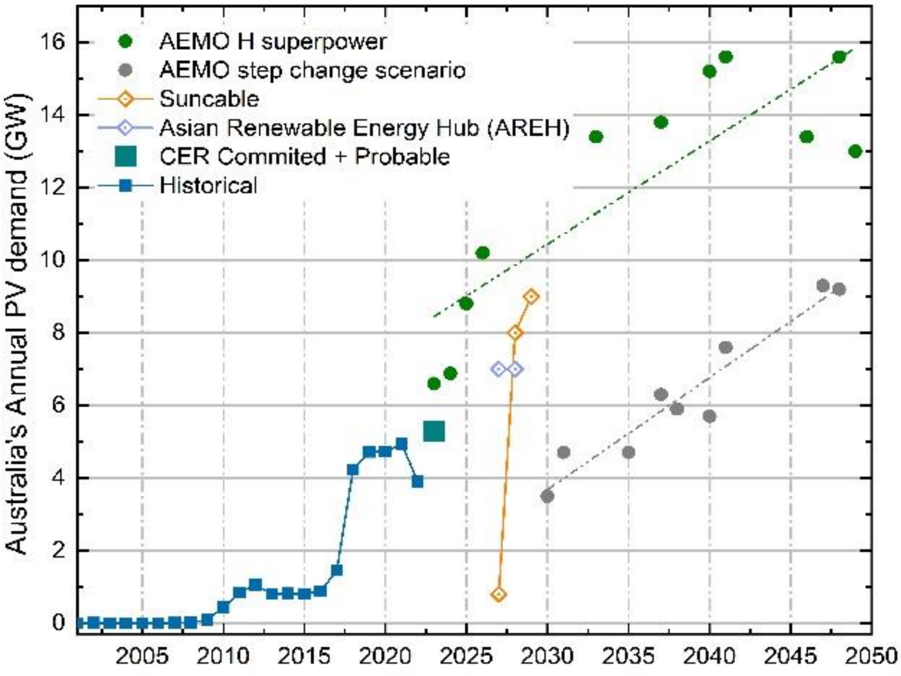

Figure 5: Australia's Solar PV annual demand forecast. Sources: AEC[47], AEMO[48] and APVI[49].

Evidently, even the "step change" scenario appears too cautious, as Australia has already exceeded the 5 GW per year installation target in the past, and large-scale private initiatives, such as the Sun Cable project and the Asian Renewable Energy Hub, which have significant PV capacity requirements, have not been factored in. Figure 5 shows the total targeted volumes of each of these projects as publicly announced, divided by a possible timeframe of installation. It is, therefore, more credible to expect between 10 GW and 15 GW additional solar capacity per annum from 2030 onwards.

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[46] Australian Government, https://www.globalaustralia.gov.au/industries/net-zero#:~:text=Rewiring%20the%20Nation%20provides%20A,82%20per%20cent%20by%202030 , viewed 12th May 2023.

[47] Australian Energy Council, "Solar Report", Q4 2022 and Q1 2023.

[48] AEMO, 2022 Integrated System Plan, June 2022.

[49] APVI, https://pv-map.apvi.org.au/analyses, viewed 5th April 2023.

PV SUPPLY ACROSS THE VALUE CHAIN

GLOBAL MANUFACTURING CAPACITY

Chinese companies, such as LONGi, JinkoSolar, Trina Solar, JA Solar, Canadian Solar, Risen Energy, continue to lead the solar PV manufacturing industry with the largest production facilities in the world. Figure 5 illustrates the 2023 annual production output in GW for the major players across all segments of the market, together with the share of total global annual production.

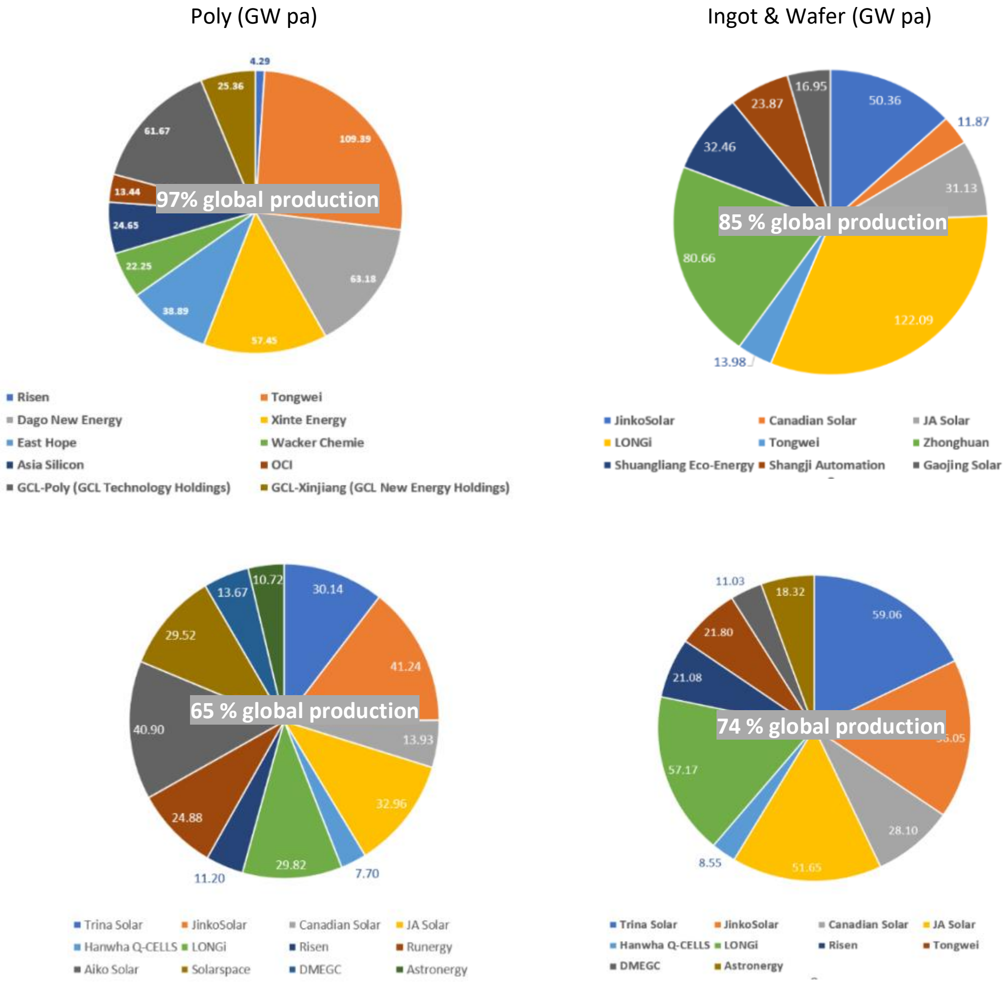

Figure 5: Top players per segment and corresponding annual production (GW p.a.) in 2023. Source: PV Cell Tech[50].

A considerable number of these players have already embraced varying degrees of vertical integration, representing considerable investment, and are benefiting from economies of scale.

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[50] PV Cell Tech, “PV Manufacturing & Technology Quarterly Report”, April 2023.

In the last decade, Chinese manufacturers have made remarkable strides in ingot and wafering expertise, and China is committed to protecting these advancements. Currently, the Chinese government is contemplating the implementation of export restrictions on solar wafers, black silicon, and silicon casting equipment. If these categories are included in the Chinese catalogue of restricted technology, manufacturers will be required to obtain technology export licenses from provincial departments in order to export these products[51].

Polysilicon: As expected, the major changes in polysilicon capacity for 2023 are concentrated in China. These expansions are financed with Chinese capital, constructed using Chinese equipment, and operated by Chinese-owned public/private entities. The domination of Chinese manufacturing of polysilicon in 2023 remains largely unchanged, with the only notable difference being a reduced proportion of production originating from Xinjiang[52]. At present, Germany's Wacker Chemie and South Korea's OCI are the only non-Chinese manufacturers with a relevant manufacturing capacity.

In 2023, there are some potential developments in polysilicon capacity outside China that may occur. Wacker's German operations may increase capacity[53], REC Silicon is planning to restart its FBR production in the US[54], Hemlock might upgrade its US plant to increase shipments to the PV industry[55], and OCI may either transport legacy OCI polysilicon plant and equipment to Malaysia or revive its dormant capacity in Korea[34].

Ingot & wafer: In terms of ingots, the capacity in China is very large, resulting in a situation where very few plants need to operate at utilization rates exceeding 90%. When it comes to wafering, China currently dominates the market in every aspect. However, there are notable expansions taking place outside of China in 2023, primarily led by Chinese module suppliers targeting the US market. These companies, such as JA Solar, JinkoSolar, and Trina Solar, are establishing ingot/wafer capacity in Vietnam to facilitate customs clearance approval in the US. The three main wafer suppliers continue to be LONGi, GCL-SI, and Zhonghuan, which have a combined market share of around 50%. Currently, there are no non-Chinese players of relevant capacity in the ingot & wafer step.

Cells: The cell production sector is also heavily dominated by Chinese companies such as Trina Solar, Aiko Solar, JA Solar, Jinko Solar, and LONGi, who collectively hold almost 60% of the market share. For 2023, it is projected that the top four module suppliers, namely LONGi, Trina, JA, and Jinko, will each surpass the 50 GW production mark, an accomplishment that is unlikely to be matched by any other players in the industry. Hanwha Q Cells, headquartered in South Korea, is the only non-Chinese player in this step of the silicon PV value chain with relevant manufacturing capacity. US company First Solar is the main player in the thin-film market segment with manufacturing facilities in the US, Malaysia, Vietnam and soon in India. However, its combined annual capacity by the end of the year will only reach the 12 GW mark which again pales in comparison with the leading four Chinese companies.

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[51] PV magazine, https://www.pv-magazine.com/2023/01/30/china-plans-to-introduce-restrictions-on-polysilicon-wafer-exports/ , 16th May 2023.

[52] PV Cell Tech, "PV Manufacturing & Technology Quarterly Report", April 2023.

[53] PV magazine, https://www.pv-magazine.com/2022/05/27/wacker-to-expand-silicon-metal-production-in-norway/, viewed 5th May 2023.

[54] PV Tech, https://www.pv-tech.org/rec-silicons-planned-moses-lake-reopening-underpinned-by-inflation-reduction-act-ceo-says/, viewed 5th May 2023.

[55] PV Cell Tech, "PV Manufacturing & Technology Quarterly Report", April 2023.

Modules: The domination of Chinese manufacturers is still strong in module manufacturing. However, as a result of the Inflation Reduction Act (IRA), Hanwha Q Cells has revealed plans for the largest investment to date in the US, involving the construction of a fully integrated plant with an annual capacity of approximately 3 GW[56]. The construction of this plant is set to commence in 2023, with the goal of achieving fully operational status by 2025, and other non-Chinese module manufacturers in the US are going to follow suit. In Europe, Enel has also announced new annual production capacity of 3 GW in Sicily[57]. However, these developments are relatively small compared to the bigger picture (Figure 6). Furthermore, and because of enduring substantial anti-dumping and countervailing tariffs when exporting to the US, Chinese solar cell and module manufacturers opted to shift their production facilities to Southeast Asian countries to access the US market. Nevertheless, the introduction of the IRA has now also enticed major Chinese producers like JA Solar and Jinko Solar to expand their manufacturing capacities inside the US[58].

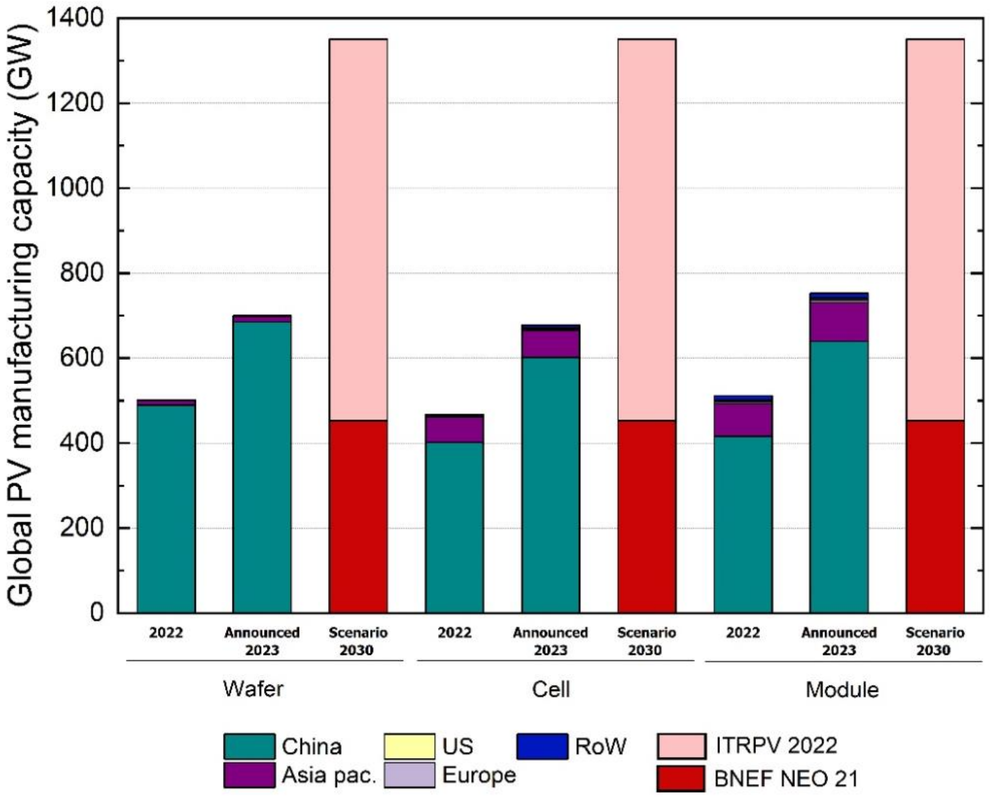

Figure 6: PV manufacturing capacity by country/region: current, announced/expected in 2023 and required according to BNEF's Green scenario and ITRPV's broad electrification scenario. Source: PV Cell Tech[59].

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[56] PV magazine, https://www.pv-magazine.com/2023/04/18/us-inflation-reduction-act-triggers-plans-for-46-new-factories-says-industry-association/, viewed 5th May 2023.

[57] Enel, https://www.enel.com/media/explore/search-press-releases/press/2022/04/enel-green-power-signs-grant-agreement-with-the-eu-for-solar-panel-gigafactory-in-italy , viewed 1st May 2023.

[58] Solar Builders, https://solarbuildermag.com/news/module-manufacturing-moves-this-month-show-power-of-u-s-policy/, viewed 16th May 2023.

[59] PV Cell Tech, "PV Manufacturing & Technology Quarterly Report", April 2023.

AUSTRALIAN MANUFACTURING CAPACITY AND INTEREST

The only current PV module manufacturer in Australia is Tindo Solar with an annual production capacity of approximately 150 MW,[60] although current annual production is only in the vicinity of 50 MW. With full utilisation of the production line, this represents only 4% of the current demand for solar in Australia.[15]

A prospective cell and module manufacturer in Australia is Sundrive, who expects the first phase of manufacturing to be cell metallisation and module assembly with an annual production capacity of 1 GW. Subsequent phases could move further up the supply chain to add complete cell fabrication, ingots and polysilicon production heading towards 5 GW annual production capacity.[61]

It is noted that other players such as Fortescue Future Industries are also considering PV manufacturing, but using thin-film perovskite technology.[62]

Further upstream, the mg-silicon production of Simcoa in WA is sufficient as an input for approximately 17 GW worth of annual polysilicon production for local solar, although it currently has other offtakers.

TECHNOLOGY OPTIONS ACROSS THE VALUE CHAIN FOR VIABLE, RELEVANT AND TIMELY SUPPLY

There are several key interdependent considerations for the chosen technology to meet the three assessment principles of *timely, relevant* and *viable*.

Timely: To reach 60 TW of cumulative installed capacity by 2050 globally, an average of 2 TW per year would need to be installed from now until 2050. However, with the industry currently deploying around 300 GW per year, it will take 5-10 years to build up the global manufacturing capacity to TW scales of annual deployment. A realistic scenario is that in 2035-2040 there will be a couple of TW of capacity, and by 2050 the capacity could potentially reach ~4.5 TW per year in line with the ITRPV (see Chapter 0).

To have a reasonable chance of meeting the net-zero target by 2050, the focus should be on technologies that are already produced at multi-GW scale, such that TW scales of annual manufacturing can be achieved by 2030. In addition, for the technology to be low cost and minimise emissions, PV systems must continue to operate for at least 25 years. The technology must also be capable of attracting financial backing ('bankable') with sufficient field data to ensure 25-year operation in the field can be achieved. These two aspects limit potential candidates in the short term to wafer-based silicon PV panels (PERC, TOPCon and SHJ)[63] and cadmium-telluride (CdTe) thin-film modules. Without any commercial products available on the market, recently developed tandem devices and thin-

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[60] Renew economy, https://reneweconomy.com.au/australias-only-solar-manufacturer-launches-11m-production-and-innovation-facility/ viewed 15th May 2023.

[61] Renew economy, https://reneweconomy.com.au/solar-innovator-sundrive-maps-out-plan-for-5gw-of-australian-pv-manufacturing/ , viewed 15th May 2023.

[62] Renew economy, https://reneweconomy.com.au/fortescue-to-fund-new-solar-factory-as-it-lays-bet-on-thin-film-solar/ , viewed 15th May 2023.

[63] PERC = Passivated Emitter and Rear Cell, TOPCon = Tunnel Oxide Passivated Contact, SHJ = Silicon Hetero-Junction

film perovskite variants are ruled out. This is in alignment with expectations from the ITRPV, whereby the expected market share for tandems in 2033 is <5%, and no expected market share for perovskites.

There are also several stability issues that need to be solved for both perovskites and tandems to ensure long-term reliability, which will require a number of years of field-data once commercially viable products have been developed in order to become ‘bankable’.

Relevant: The chosen technology must also have minimal challenges related to the availability of raw materials to allow TW scales of global annual manufacturing. Many PV technologies can be instantly ruled out for being capable of a TW scale market due to the scarcity of the absorber material, such as cadmium-telluride thin-film, which already uses 40% of global tellurium supply for less than 10 GW of annual PV manufacturing. This criterion also rules out alternative III-V semiconductor materials such as gallium arsenide.

Viable: A viable technology requires consideration of both efficiency and cost. The efficiency must also be reasonable to reduce balance of systems costs, which now make up an increasing portion of total PV costs, with decreasing solar module costs. With current mainstream silicon PV modules at 20-22% efficiency, low-efficiency thin-film technologies (with the exception of First Solar CdTe modules at about 18%) can be ruled out for large-scale use, due to increasing balance of systems costs, driven by the need for more area related materials for balance of systems components (civils, wiring, labour etc).

For CdTe, only one company (First Solar) produces this technology, and it is protected by a suite of patents. Hence, while it is possible for First Solar to set up manufacturing in Australia, within the S2S Study it is not possible to assess the supply chain requirements. For this technology, the current global supply of tellurium will not be sufficient to support PV manufacturing requirements in both Australia and the US. The use of scarce materials in high quantities also risks future increases in material cost to meet demand, thereby affecting financial viability.

A summary of the timeliness, relevance and viability of the technologies is shown in Table 1. Considering these attributes, the S2S Study focuses on using wafer-based crystalline silicon solar cells, which rely on either purified sand or quartzite as the base material. Once a silicon wafer-based solar industry is established, it will serve as a supporting platform for the development of more advanced technologies that have not yet reached the Commercial Readiness Index required for mass manufacturing. A silicon mainstream solar industry will build up an ecosystem of equipment suppliers, support services, skilled workforce, and investment. This ecosystem will enable other solar technologies to grow and become successful. The spill over effects of a successful silicon PV industry will have wide positive ramifications for the solar industry as well as research and development in Australia.

	Timely		Relevant		Viable	
Wafer-based silicon	✓	~300 GW in 2022	✓	Can be TW scalable provided low silver consumption	✓	Mainstream technology in 2023 at US$0.20/W.
Cadmium telluride	✓	9.1 GW in 2022	?	Not scalable to TW scale due to tellurium scarcity	?	Assessment out of reach to S2S. First Solar partnership needed for IP.
Thin-films (without First Solar CdTe)	?	No significant market share	✓	Provided the use of abundant materials (e.g. thin film silicon)	?	Higher efficiencies needed to reduce cost
Perovskites	?	No commercial product available at scale	?	Need to replace indium	?	Need work on reliability/stability to ensure a bankable product with a 25-year lifetime
Tandem	?	No commercial product available at scale	?	Need to replace indium	?	Need work on reliability/stability to ensure a bankable product with a 25-year lifetime
III-V materials	?	Not in mass production	?	GaAs limited by availability of gallium	?	High cost of scarce materials and deposition technology

Table 1: PV technology comparison using S2S criteria. Sources for annual production capacity and prices. Sources: PV Cell Tech[64] and PVInsights[65].

POLY-SI

Purification of metallurgical grade silicon towards 6-nines (99.9999%) to 11-nines (99.999999999%) purity for solar-grade polysilicon is energy intensive. The mainstream method used to purify to metallurgical grade uses a modified Siemens process, with heat and energy recovery, to yield an electricity requirement in the vicinity of 30 – 50 kWh per kilogram of polysilicon. It is noted that other technologies with reduced electricity requirements do exist, such as the fluidized bed reactor (FBR) technology, with a requirement of approximately 20 kWh/kg. However, this technology is restricted with patents owned by REC Silicon, and only has approximately 5% market share. In addition, benefits of reduced electricity consumption can largely be eliminated by a larger fraction of unusable silicon from the FBR process. Efforts to reduce the price and emissions intensity of electricity will also reduce future potential benefits of the FBR technology over the Siemens technology. The process for converting mg-Si into solar-grade polysilicon, and a factory, is shown in Figure 7.

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[64] PV Cell Tech, "PV Manufacturing & Technology Quarterly Report", April 2023.

[65] PV Insights, http://pvinsights.com/, viewed 15th May 2023.

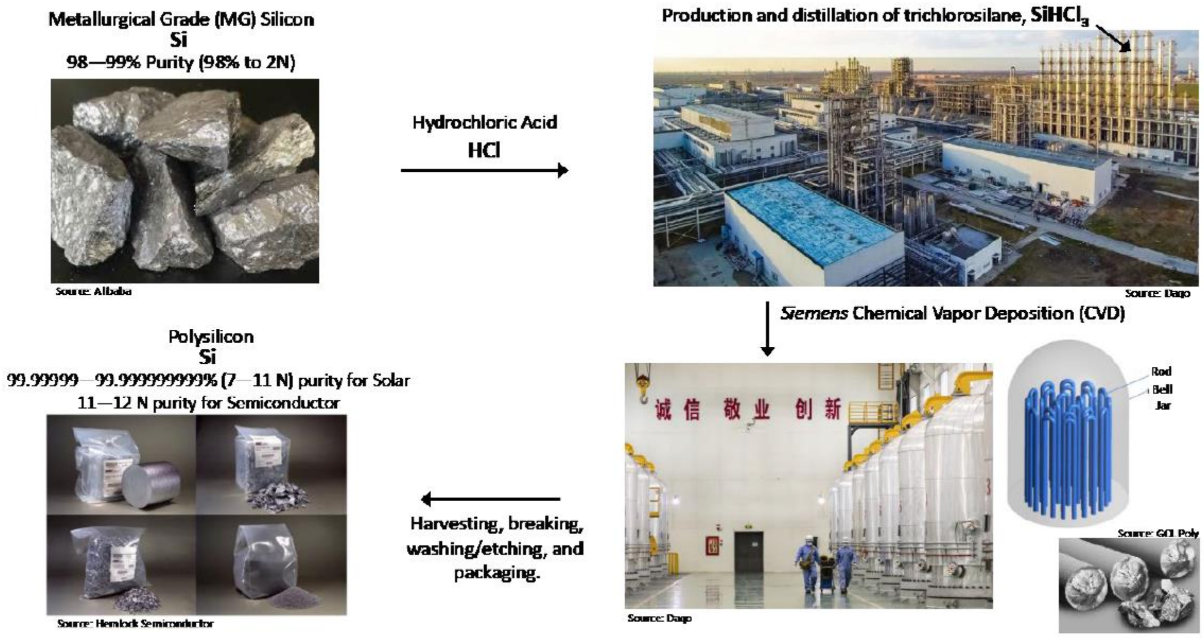

Figure 7: Steps for the purification of mg-Si to poly-Si using the Siemens chemical vapour deposition process, the gas purification and deposition processes are carried out at large chemical factories. Source: US DOE[66]

Alternative methods like upgraded metallurgical grade silicon can potentially reduce cost further, but often suffer from lower material quality, which is undesirable with the continual shift towards higher efficiency panels, whereby quality of the bulk silicon material plays an increasing role. For these reasons, in this S2S Study, the focus is on polysilicon production via the Siemens route.

INGOT/WAFERS

The dominant ingot technology is Czochralski (Cz) grown single crystalline silicon. P-type wafers are primarily gallium-doped, while emerging n-type wafers are phosphorus-doped. Ingot growers can relatively quickly change between producing n-type and p-type ingots, and therefore, can rapidly respond to specific wafer demands by industry. Currently, ingots are heading towards 295mm diameter to produce 210mm wafers. One alternative ingot technology is the float-zoning method. However, float-zoned silicon is too expensive for solar production. The second alternative is ‘cast’ and ‘directionally-solidified’ silicon. Although this material is cheaper to produce than a Cz ingot, the material is typically multi-crystalline, and on average, has a much lower quality than that from Cz ingots. This translates to lower cell efficiencies and has been phased out by the PV industry with the move to higher efficiency cell technologies, which are more sensitive to incoming wafer quality. For these reasons, the S2S Study focuses on Cz grown mono-crystalline silicon.

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[66] US Department of Energy, “Solar Photovoltaics - Supply Chain Deep Dive Assessment”, page 24, published 24th Feb. 2022

Wafering is completely dominated by diamond wire sawing, with a substantially reduced cost and reduced kerf-loss[67] compared to previous sawing methods. This technology is most suited to mono-crystalline silicon due to the texturing method used being relatively unaffected by the change of sawing method, in contrast to cast multi-crystalline silicon which is more susceptible to breakage using diamond wire technology. With complete market dominance by diamond wire sawing, the S2S Study focuses exclusively on this process.

Both Cz ingot manufacturing and diamond wire sawing are well known technologies and the individual processing units are comparatively small, however, ingot and wafer manufacturing facilities are set-up at a multi-GW scale to leverage efficiencies from economies of scale and manufacturing excellence. The process flow for Cz ingot manufacturing and diamond wire sawing is shown in

Figure 8. An ingot factory and illustration of the wire sawing method are shown in Figure 9.

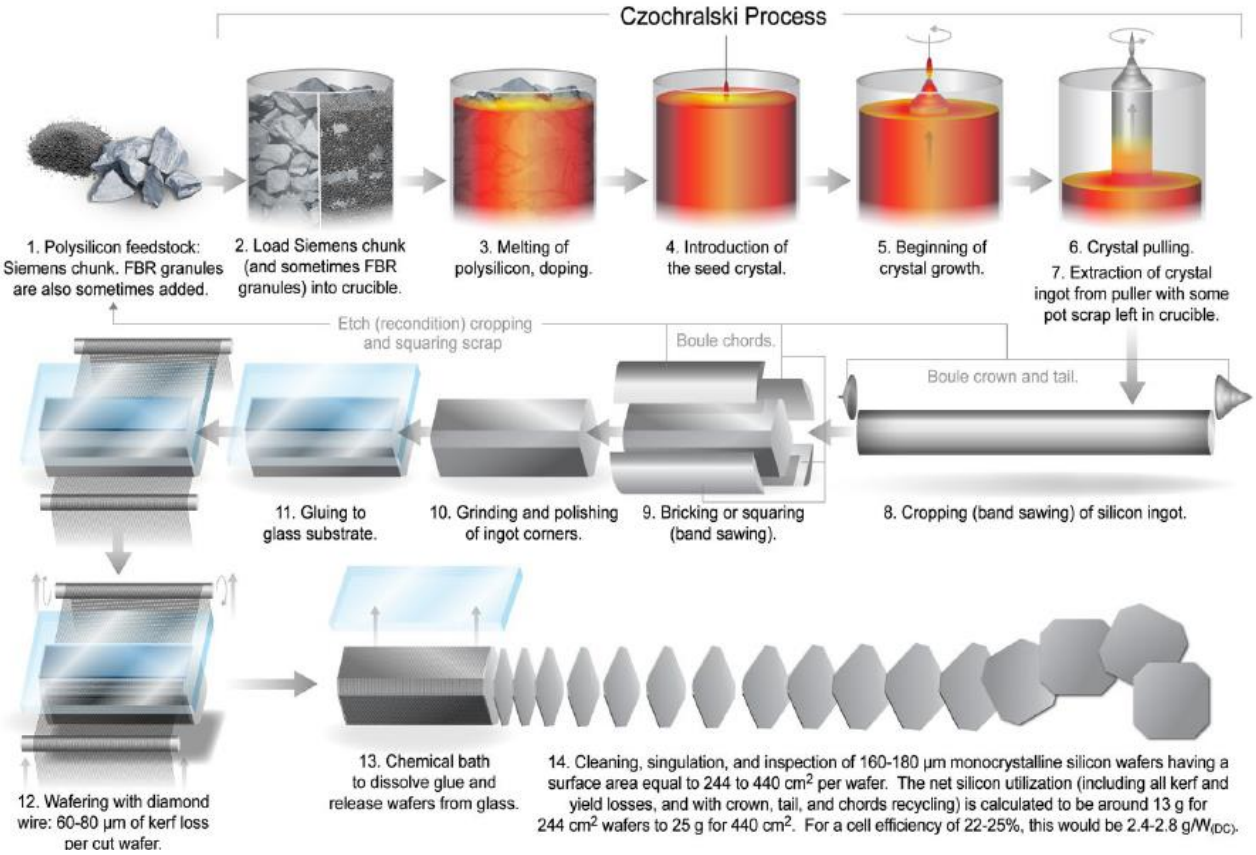

Figure 8: Process flow making mono-crystalline wafers. Source: US DOE[68]

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[67] The amount of silicon material wasted during the slicing process.

[68] US Department of Energy, "Solar Photovoltaics - Supply Chain Deep Dive Assessment", page 30, published 24th Feb. 2022

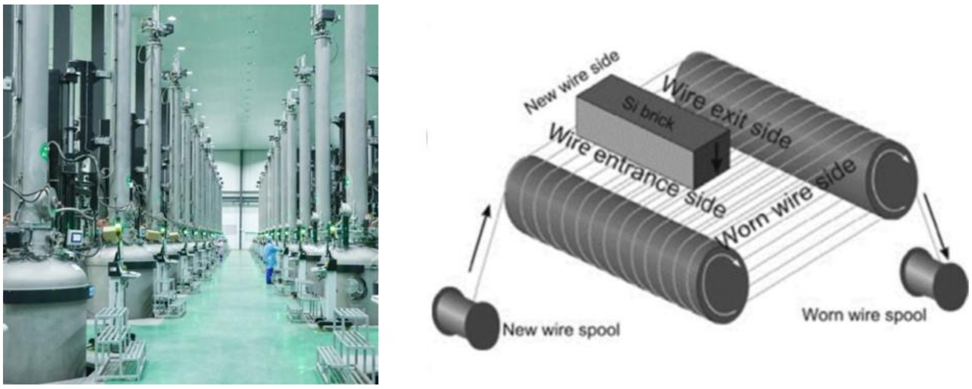

Figure 9: Ingot manufacturing facility (left) and wafer sawing method (right)

Over the last decade Chinese companies have developed significant know-how with regard to equipment as well as manufacturing processes in the field of ingot and wafer manufacturing. China is now seeking to prohibit the export of technology used to produce M10 and G12 silicon wafers[69], which are in high demand.[51] This move will likely cement China's market leadership position while also slowing down the process of bringing the solar supply chain back onshore to regions such as Europe, India, and the US.

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[69] Solar Power World; "The two new main wafer sizes that have dominated the market are the M10 (182-mm) and G12 (210-mm)", https://www.solarpowerworldonline.com/2023/01/downstream-players-adapt-to-irregular-panel-sizes-entering-all-markets/#:~:text=The%20two%20new%20main%20wafer,G12%20(210%2Dmm), viewed 22 May 2023

CELLS

Solar cells are manufactured in highly automated clean room facilities (see Figure 10). The typical scale of a solar cell manufacturing facility is now some 100 MWs to a several GWs.

Figure 10: Highly automated solar cell manufacturing line in a clean room facility

The current mainstream silicon solar cell technology is PERC technology, first developed at the University of New South Wales in the 1980s[70], with 80% market share. The process flow for manufacturing 'Passivated Emitter and Rear Cell' (PERC) solar cells is shown in Figure 11.

By 2026, 'Tunnelling Oxide Passivated Contact' (TOPCon), introduced in 2013,[71] is expected to take over as the dominant technology, seen as an upgrade from PERC with a largely similar process flow and equipment requirement. Therefore, TOPCon can benefit from the knowledge and equipment base for current mainstream PERC technology.

The third key silicon-based technology is the silicon heterojunction (SHJ) technology, which requires a completely different process flow and equipment list than PERC/TOPCon, and is only expected to reach 15% market share by 2030. However, the use of indium for transparent conductive oxide layers in industrial SHJ solar cells rules it out as a candidate for terawatt-scale manufacturing. Although alternative materials do exist, they often introduce new challenges and reduce the potential efficiency benefits of using the SHJ cell technology compared to the mainstream technology. In addition, at the module level, current industrial SHJ modules do not have a superior efficiency over industrial n-type TOPCon modules.

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[70] Solar Power World, https://www.solarpowerworldonline.com/2016/07/what-is-perc-why-should-you-care/#:~:text=First%20developed%20in%20Australia%20in,side%20of%20a%20solar%20cell, viewed 15th May 2023

[71] Solar Power World, https://www.solarpowerworldonline.com/2022/04/what-is-topcon-solar-panel-technology/, viewed 15th May 2023

From this analysis, the S2S Study has narrowed its focus to n-type TOPCon technology, which is currently being rapidly deployed throughout the industry via new production capacity. This study will draw on the similarities to PERC and the more readily available information, based on its current market dominance. An issue related to TOPCon that still requires resolution, and indeed for other silicon solar cell technologies, is silver consumption. Addressing this will require continual improvements in screen printing technology, as are occurring in the industry. A particular concern for TOPCon is that the current industrial implementation uses approximately 60% more silver than PERC, leading to a higher module manufacturing cost, despite higher module efficiencies, which will need to be addressed in future improvements of the technology.

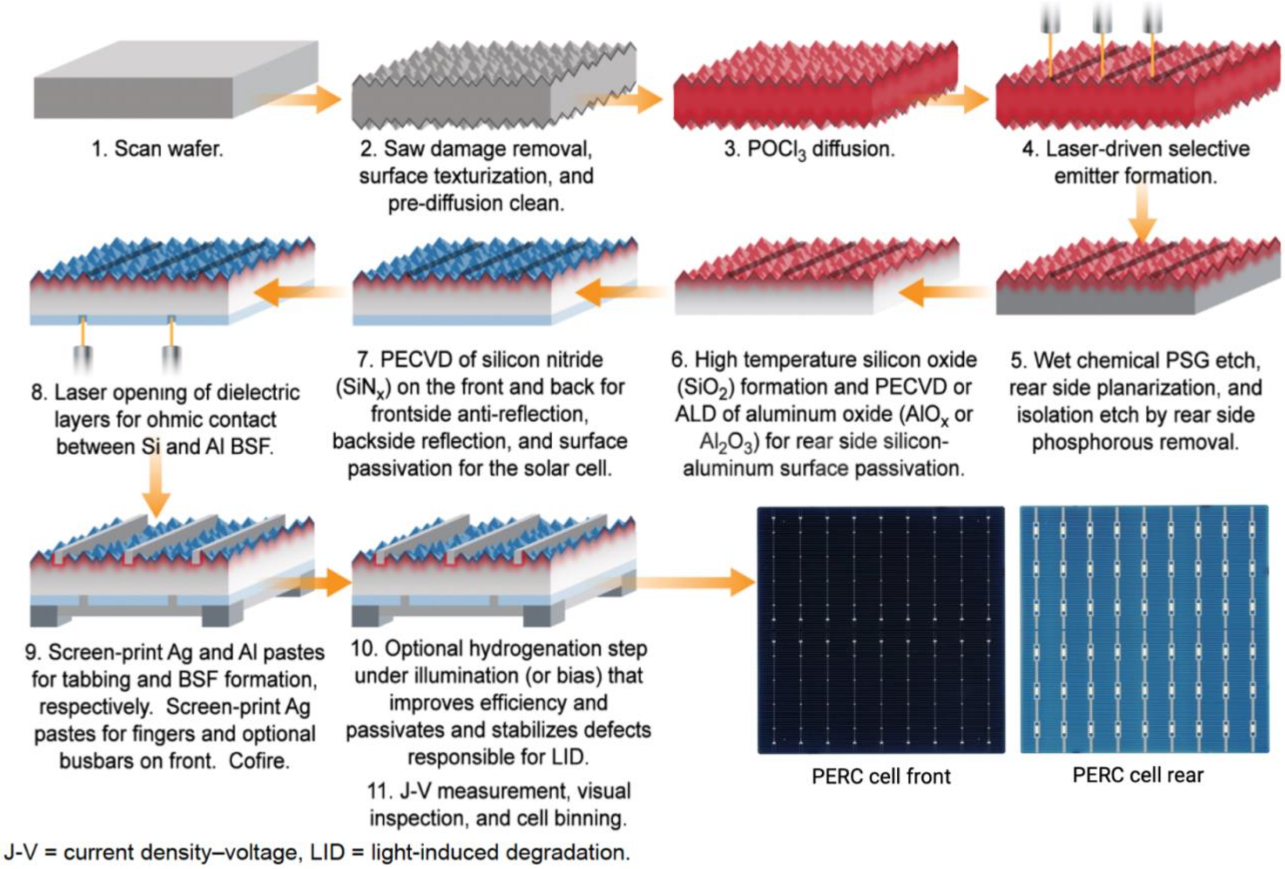

Figure 11: Process flow for manufacturing standard full-area PERC cells. Adapted from NREL.[72]

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[72] US National Renewable Energy Laboratory, "Photovoltaic (PV) Module Technologies: 2020 Benchmark Costs and Technology Evolution Framework Results", page 10, Published November 2021.

MODULES

There are two dominant module constructions in the PV industry, namely monofacial and bifacial module technologies. However, both of these constructions are similar in that they both use a glass sheet at the front of the module to protect the solar cells. Both module types also typically use bifacial and 'half-cut' cells because it is the most cost-effective technology at present. The module construction mainly differs in the use of materials at the rear, affecting the ability of the module to receive light from the rear of the panel.

Typically, monofacial module technologies use a white backsheet. These modules are typical for residential rooftop applications. To limit the panel weight to below 25 kg for ease of installation on rooftops, rooftop panels use a smaller format than utility-scale panels.

Modules for utility-scale PV are typically bifacial, with a glass-glass construction, increasing the total weight of the solar panel for a given power output, but increasing the yield per unit area. Without the same weight restrictions as for residential rooftop PV, utility-scale PV modules tend to be larger than residential rooftop panels. Figure 12 shows an image of the front and rear of mono-facial and bifacial PV modules.

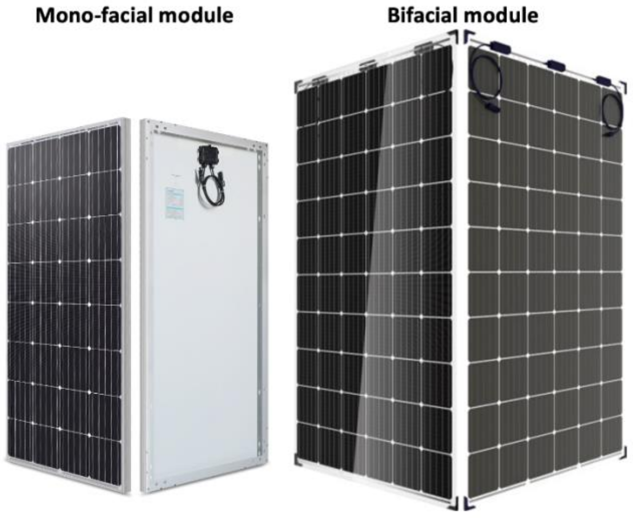

Figure 12: Front and rear of mono-facial and bifacial modules

An alternative 'glass free' module technology is a lightweight module technology by Sunman, reducing module weight by approximately 70%. However, with limited deployment to date, higher costs and a current annual production capacity of 1 GW,[73] the focus of the S2S Study is on mainstream glass PV module technology, with a view to adoption of other technologies over time. To cover both residential and utility scale PV applications for future PV deployment in Australia, the S2S Study focuses on both a mono-facial rooftop PV module and a bifacial utility scale module.

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[73] PV Magazine, https://www.pv-magazine-australia.com/2022/01/13/sunman-opens-1gw-lightweight-pv-module-factory/, viewed 15th May 2023.

Due to the various wafer size options, a large number of potential module sizes and cell configurations exist. For simplicity, in this study the focus will be on the following module configurations.

1) A mono-facial residential panel with 120 half-cut cells from 182mm wafers. A residential panel with this cell configuration can have a power output in the vicinity of 440 – 460 W.
2) A bifacial utility-scale panel with 144 half-cut cells from 182mm wafers. A utility scale panel with this cell configuration can have a power output in the vicinity of 530 – 550 W.

The process flow for manufacturing glass encapsulated PV modules in shown in Figure 14. In the past, module assembly was labour intensive, which gave countries with low labour costs a production cost advantage. Modern module assembly lines, however, are fully automated, which lends itself to economies of scale and facilities to manufacture 100 MWs to GWs of solar modules. An example of a highly automated module assembly line is shown in Figure 14.

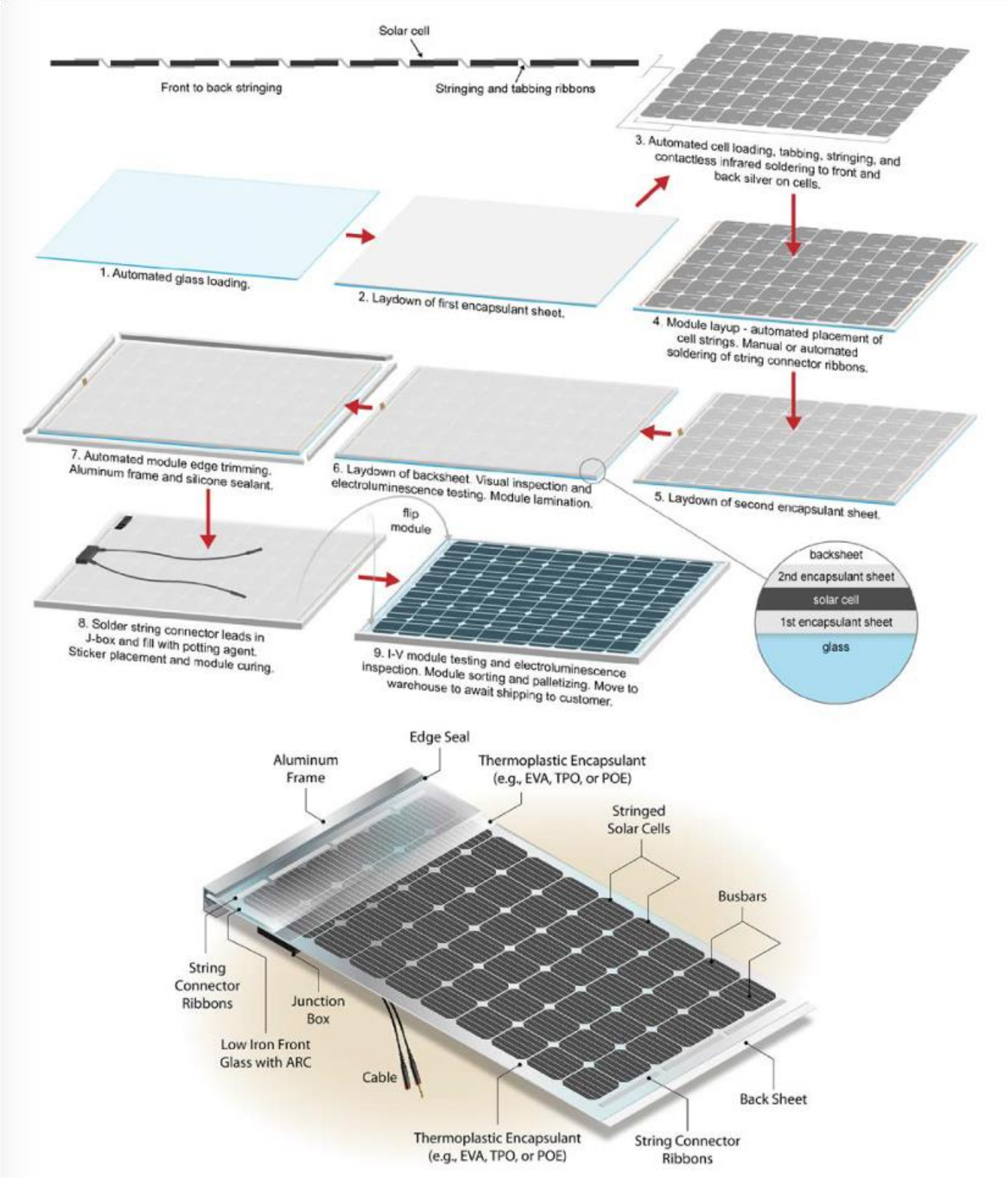

Figure 13: Process flow for a glass/backsheet solar module assembly. Source: NREL[74]

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[74] US National Renewable Energy Laboratory, "Crystalline Silicon Photovoltaic Module Manufacturing Costs and Sustainable Pricing: 1H 2018 Benchmark and Cost Reductions Roadmap", page 32, published February 2019.

Figure 14: Highly automated solar module assembly facility

TECHNOLOGY FOCUS SUMMARY

In summary and highlighting the importance of adopting a realistic approach towards achieving Australia's renewable energy goals, the S2S Study focuses on technologies that are already produced at a multi-gigawatt scale, allowing for terawatt scales of annual manufacturing globally by 2030. At each step, the technology is chosen to meet certain criteria to ensure viability, relevance and timely deployment. This implies minimal challenges related to the availability of raw materials, ruling out technologies that rely on scarce absorber materials. Additionally, the technology should demonstrate reasonable efficiency levels to reduce balance of systems costs. Considering these attributes, the S2S Study focuses on wafer-based crystalline silicon technology (see Table 2).

The S2S Study acknowledges the potential for incremental innovation within the established technology scope. This includes exploring advancements such as copper contacting, bifacial technology, and glass-free technology. These innovations will be deemed within scope as long as their adoption complements rather than replaces the existing investments in baseline facilities, thereby enhancing their functionality. The S2S Study therefore aims to explore the establishment of a manufacturing platform for the industry on which other Australian innovations, including those already supported by the Australian Government, will be able to build[75].

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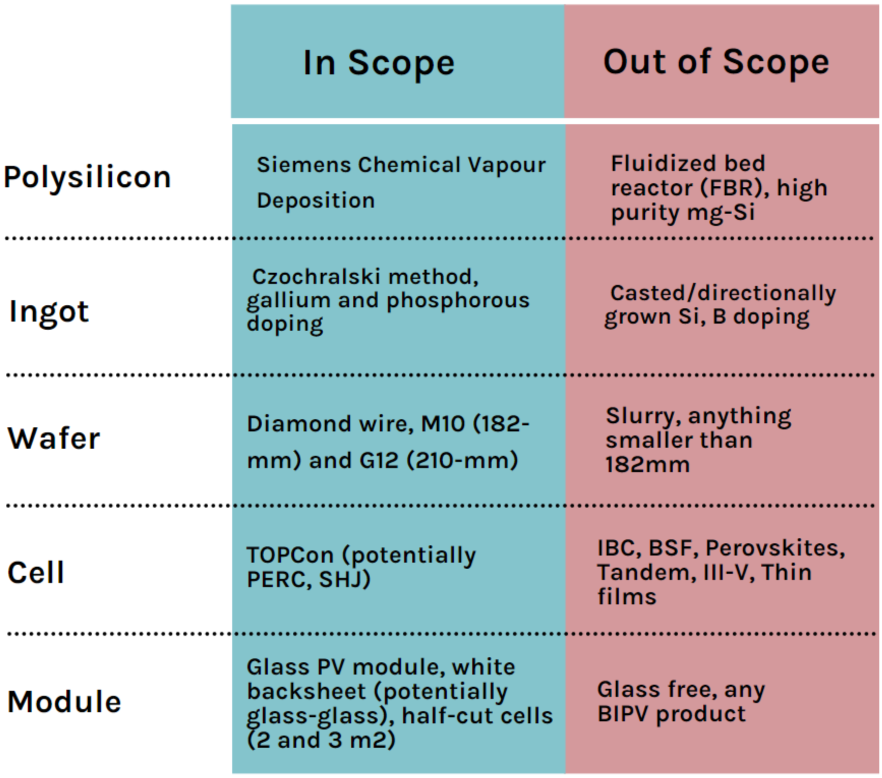
[75] For example the Australian Renewable Energy Agency supports the development of copper plating for the manufacturing of solar cells by Australian start-up SunDrive to drastically reduce the consumption of silver, https://arena.gov.au/projects/sundrive-copper-metallisation-demonstration/ viewed 29 May 2023



	In Scope	Out of Scope
Polysilicon	Siemens Chemical Vapour Deposition	Fluidized bed reactor (FBR), high purity mg-Si
Ingot	Czochralski method, gallium and phosphorous doping	Casted/directionally grown Si, B doping
Wafer	Diamond wire, M10 (182-mm) and G12 (210-mm)	Slurry, anything smaller than 182mm
Cell	TOPCon (potentially PERC, SHJ)	IBC, BSF, Perovskites, Tandem, III-V, Thin films
Module	Glass PV module, white backsheet (potentially glass-glass), half-cut cells (2 and 3 m2)	Glass free, any BIPV product

Table 2: S2S Study scope summary.

IMPLICATIONS FOR THE PHASE 2 REPORT

The rapid growth of solar demand in Australia from currently about 4 GW pa to between 10 GW and 20 GW pa forecast for the years 2030 to 2050 will require a stringent focus on securing solar module supply, otherwise Australia's decarbonisation targets and the ambitions of becoming a renewable energy superpower are seriously at risk. This risk is exacerbated by the fact that the world's demand for solar power will increase from about 300 GW pa to between 1TW to 4 TW pa over that timeframe, depending on the degree of electrification.

As discussed above, Australia has three levers to manage this risk:

i. **Depend on China:** Australia can continue depending on China, which as a nation has supplied the world with affordable, high-quality solar cells for the last decade.
ii. **Others solve the issue**: Australia can hope to diversify the supply of solar modules from other regions, like the USA, Europe, India etc.
iii. **Take some control back**: Australia could build up manufacturing capacity across parts or the entire solar value chain. This could be facilitated through bilateral agreements or collaborative ventures with other nations, enabling active involvement in a diversified global solar supply chain.

In Phase 2 of the S2S Study, the third lever will be assessed in detail to establish if there is a credible future state where some or all segments of solar manufacturing are able to satisfy the three principles established for this study:

a) *Viable*: The manufacturing step in the value chain needs to be globally competitive and be economically viable long term.
b) *Relevant:* The manufacturing facility needs to have a scale that is fitting for future Australian and global PV demand.
c) *Timely*: The manufacturing capacity needs to be set up within a timeframe that is necessary to achieve net zero by 2050.

The manufacturing technology chain, which will be the subject of the assessment in Phase 2, is the silicon wafer based solar module technology produced using the Siemens poly-Si production process, diamond wafer sawing, n-type TOPCon cell technology and glass module encapsulation. The Techno-Economic Assessment and subsequent Business & Policy Assessment will be carried out with a wide range of industry partners and collaborators. This will include assessment of the production scale and investment required at each stage, the parties which may be interested in investing as well as the opportunities available across Australia to support the development of a baseline manufacturing industry.