MONO AND MULTI CRYSTALLINE SILICON – SUPPLY CHAIN ANALYSIS AND BOS IMPACT

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ABSTRACT: There is general recognition that higher Conversion Efficiency (CE) has benefits throughout the value chain of PV manufacturing and system installation. However, typically cost sensitivity has driven the strong demand for lower cost cells and panels. In general, mono-c-Si provides the opportunity for higher CE, as well as improved yield from less wafer breakage. This paper presents the broader view supporting the notion of advantages for higher CE based on the positive impact on the full value chain extended to electricity production. Higher CE benefits both $/W and LCOE since there are benefits to increasing the CE even with some limited associated increase in manufacturing cost. The advantages of mono with the higher CE are presented as well as some of the developing drivers for increased adoption. In particular, the SiGen approach is highlighted for its ability to allow increased market penetration of mono with additional advantages stemming from the intrinsic nature of the kerf-free wafers. These advantages include: low starting poly Si material usage, the complete absence of micro-cracks, and improved TTV, as well as the ability to dramatically lower the kg/W metric. A representative comparison to Diamond Wire is addressed. This paper will provide a descriptive analysis of the crystalline silicon value chain. Even though the previous rapid market expansion favored the lower cost multi-c-Si, it appears increasingly beneficial to implement mono-c-Si because of the various advantages.

1 INTRODUCTION

The PV industry grew approximately 90% in shipments in 2010 achieving about 18GW of new installations. This strong surge in demand has accelerated the additional production coming on stream at all levels of the supply chain. The debate in the PV industry is not if the prices will decline, but by how much, how rapidly, and with what characteristics in production. Positioning for an oversupply and for ASP declines is normally seen as a commoditized and unattractive business model environment. However, that view normally pertains to industries where there is not much opportunity for market share gains, or for segments with limited growth. For the case of PV there are approaches which can allow for improved market share growth and positioning.

Given the increased focus on the final product (energy production) of a solar installation, there is increasingly a shift in focus to new metrics such as LCOE. The LCOE metric takes into account the cost elements of the panel, the BOS, and lifetime of the system, the overall degradation (i.e. irreversible efficiency drops), the overall energy harvest, and the general cell lifetimes. Thus, the cost structures are becoming more sophisticated in terms of the inputs to what constitutes a viable economic driver for market adoption. Instead of just looking at the least expensive panel in $/W, a more refined view is necessary which considers the energy harvesting potential, the reliability, the cost benefit of higher efficiencies, etc. In this regards, the industry is maturing in order to adjust to the environment where installation subsidies and other support mechanisms are being eliminated.

Previously, the rapid growth in demand has favored the multi-c-Si suppliers because of the lower entry barrier even with the lower quality and technology requirements. Multi-c-Si has a reduced cost because of the less expensive upstream ingot casting steps as compared with the Czochralski (CZ) process. Recent developments of reduced cost CZ are being aggressively pursued but overall the process remains more expensive. However, there are other considerations with regards to multi-c-Si. It is not possible to wire-saw multi-c-Si to the thinner wafer dimensions, there is more yield loss in the cell-to-module manufacture, and there are strong indications that it can achieve only a fraction of the high CE levels made possible by improved processes. For instance, the multi-c-Si has reduced effective minority carrier lifetimes – a fundamental barrier to optimize solar cells CE. The lower cost up-stream model may be attractive for short-term market growth; however it may suffer in cases where overall performance becomes more important than upfront costs.

Because the view of just obtaining the lowest cost panels is in need of re-examination, it is valuable to evaluate which materials and technology choices enable the best overall energy harvesting at lowest cost. It is important to examine the materials which can contribute to better and more stable performance, and more supply chain cost reduction. More specifically, there is a renewed interest in exploiting the opportunities of mono-c-Si which can provide many of the necessary improvements to achieve the lower overall LCOE. This paper presents an analysis of the benefits of increased mono-c-Si usage in the value chain.

2 EVOLVING SOLAR VALUE CHAIN

2.1 Energy production

The Solar value chain is now extending past the system to include energy production. While $/W metric is still primary, the more sophisticated LCOE measure is gaining broad acceptance as more relevant to the energy production mode.

- Energy harvesting is important: kW-hr/kW installed
- LCOE is the new metric and will impact considerations up the value chain
- Now necessary to evaluate the paths to achieve better overall LCOE

- Including panel performance, BOS costs, as well as energy harvesting
- Use of kerf-free wafering approaches

Previously the solar value chain went from poly-to-panel, which was then updated to go from poly-to-installation. Now given the developing market conditions where the final product is the electricity generated, the value chain is evolving to include the end point of service, i.e. the

production of energy

Figure 1: Extended solar value chain including the end service:

2.2 LCOE: increasing emphasis

Because the value chain has extended to the final point of service, the various choices for technology and products may be affected by the end point. The overall sequence remains the same but now the metric is not simply the $/W that was common for the original value chain up to the system. In this case, the $/W metrics need to be folded into a more sophisticated view of an LCOE analysis. LCOE has always been a useful PV metric and is now being discussed with increasing frequency. It is important to note that for other segments of solar energy the LCOE metric has been an important metric. In particular, for the concentrated solar markets, the up-front costs are typically much higher than PV, so the more appropriate basis for comparison has been the LCOE. For Concentrated PV (CPV), and for Concentrated Solar Power (CSP) which uses sunlight to heat a medium to generate steam, the LCOE metric has been the basis for evaluation. Prior analyses use metrics beyond the $/W to compare between competing solar approaches [1]. As an example, Figure 2 gives a representative comparison of LCOE at different levels of solar irradiance for c-Si vs. CPV and CSP [2].

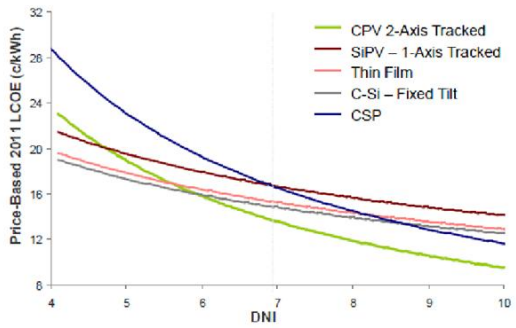

Figure 2. The LCOE metric as a function of Direct Normal Incidence [ref: N. Hartsoch]

The same considerations come to play for the various elements in the flat plate PV domain. In this domain, the key considerations include the choice of starting materials for wafer fabrication and its impact on the value chain. In the case of the wafers, the impact of the difference in performance between multi-c-Si vs. mono-c-Si will have similar considerations as in the case of CPV and CSP.

There are advantages and disadvantages of the two major c-Si materials: mono-c-Si typically provides the higher CE, but at higher growing costs; whereas the multi-c-Si provides lower cost starting material and lower CE. Even though there are developments to increase the multi-c-Si CE's, similar improvements are being made in mono-c-Si. The broader question is which material provides the best value throughout the entire value chain for the production of energy. The view this paper develops is that in the case of mono-c-Si, there are cascading benefits due to the higher CE's that will allow for overall improved energy generation at the most cost effective levels.

3 KEY CONSIDERATIONS FOR $/W AND LCOE

The $/W is the standard metric for the value chain and reflects the basic costs of manufacturing and pricing. A typical breakdown of $/W is presented below. There is much emphasis on $/W reduction and this of course impacts the LCOE analysis. Generally the best paths are those which lower both $/W as well as LCOE. For some specific elements such as kerf-free wafering, this adds the potential to achieve reduction in both metrics, and even to extend the use of the mono-c-Si material which can provide overall benefit even if the cost is slightly higher than multi-c-Si. This overall reduction is a key point for reduced LCOE and enhanced adoption of mono-c-Si because of the cascading cost benefits down the value chain.

A representative breakdown of the $/W components is shown in the table below. Note that a generic kerf-free wafering approach provides additional benefits for that segment.

	Si Feedstock	Ingot & wafering	Cell fabrication	Module assembly
2010	$0.30-0.50/W	$0.30-0.50/W	$0.25-0.80/W	$0.35-0.70/W
2013	$0.15-0.30/W	$0.20-$0.30/W	$0.20 - 0.50/W	$0.30 - 0.50/ W
Kerf-less		$0.15- 0.20/W		

Table 1. $/W breakdown with representative numbers.

The LCOE perspective has been utilized by the industry as a measure for comparison of PV configurations. The key elements of the overall system costs for the LCOE analysis include: O&M, Capacity Factor, system lifetime, and elements such as the cost of capital.

In general achieving the best LCOE and overall performance is based on:

- Lower overall costs drive needs to lower BOS
- Better harvesting drives need for higher CE and performance
- Lower costs imply: less Si utilization – thinner wafers, kerf-free

- Materials cost reduction: Thinner wafers
- Mono-c-Si CE is ~ 5% higher CE than multi-c-Si

The use of the LCOE metric has already gained traction in the flat plate PV space. The LCOE considers the extended function of the system for electricity generation and folds in the $/W costs and other system costs over the extended lifetime of the system.

3.1 BOS considerations

Because the LCOE takes into account all of the elements for a solar installation including the BOS and the Operations and Maintenance, it is important to evaluate the elements which can improve the BOS overall even if there are some increased costs for the module. In this case, higher CE panels which may be more expensive can still lead to lower LCOE given the amortization benefits realized with higher CE.

3.2 Energy harvesting

The Capacity Factor incorporates effective energy harvesting – i.e. the amount of actual energy produced from the incident sunlight.

Given the extended value chain, it is important to examine the energy harvesting. Higher photon harvesting (production of energy) will result in a lower LCOE and the potential for a higher return on investment.

There are various ways to better harvest photons, including better cell efficiency and the use of tracking. In addition, harvesting is considered over the lifetime of a system and stability of panels as they age is also important. With these various considerations, the advantages of mono-c-Si begin to emerge in the overall analysis discussed below.

3.3 Comparative assessment by LCOE

Recent analysis by SunPower has indicated that a PV power plant with the same installed price and first year performance can yield LCOE values across a wide range depending on harvesting potential, annual degradation, system life, and O&M costs. In the analysis, the LCOE is varied from $0.23/kW-hr to $0.09/kW-hr for the higher functionality system. It becomes evident that even with higher costs from installation, it is possible to achieve a lower LCOE with better functionality compared with a lower installation cost using lower CE cells and reduced functionality. [3].

4 PATHS TO HIGHER CAPACITY FACTOR

4.1 Higher Conversion Efficiency (CE)

Of the various approaches to achieve improved energy harvesting, one of the most promising path is to utilize higher efficiency mono-c-Si wafers for area constrained configurations.

Higher CE has multiple benefits:

- Higher CE accompanied by higher stability, quality & performance
- Downstream cost benefits: 5-7% per point of CE
- Upstream: better utilization

There has been extensive discussion about the analysis to determine the downstream benefits of higher CE's. The main benefit of improved CE is a leveraging of the higher watts in the denominator of the $/W metric.

4.2 General rules of thumb

The general rules of thumb for the effects of CE to the LCOE are [4]:

- Every 1% (absolute) in efficiency is worth about $0.10/W at system level (e.g. additional process cost)
- Every 1% (absolute) in efficiency is worth about $20/kg in silicon feedstock cost
- Eliminating wafering is worth about 1.5% (absolute) in efficiency

Further advantages of higher CE

- Most of the market is roof-top or area constrained
- High CE means better amortization of fixed costs: project overhead, permitting, electrical hook-up, site mobilization
    - Particularly important for smaller systems

4.3 BOS and area dependent considerations

The arguments are already well developed for area limited advantages and for BOS savings with higher CE panels. Since the overall costs are better amortized with increased CE and energy output, most of the BOS costs will benefit from higher CE. Roughly, 5-7% BOS cost reduction will result from each one point improvement of the CE.

In addition, area dependent costs also benefit from the smaller foot print of high CE systems. This includes the wiring and conduit, the framing and support, as well as the labor and mounting. Since these are complex constructions, labor costs are substantial and are difficult to lower even with the growing amount of PV on roofs [5]. Typically, the racking materials and associated racking labor makes up about 30% of the BOS and scales with area. The remaining labor associated with the installation is anywhere from 10% to 20% of the BOS, associated with the wiring and connections. For most of the other cost elements, fixed costs are effectively reduced by increased CE. These fixed costs include engineering design and layout, permitting process, overhead, electrical hook-up, and site mobilization.

5 TRACKING CONSIDERATIONS

5.1 High CE allows for tracking implementation

Because higher CE cells allow for better cost amortization, the use of active single and dual axis trackers becomes more financially attractive. The cost requirements of trackers increase the cost of the overall system; however the LCOE analysis shows that there is nonetheless a net benefit with higher CE cells. A representative discussion can be found in reference [6].

6 ADVANTAGES OF MONO-C-SI

6.1 Mono-c-Si wafer and cell benefits

Within the context of the broader cost metrics, the advantages of mono are likely to drive increased adoption over multi. Although not all of these elements will be covered in this paper, the main advantages include:

- Improved full chain cost reduction opportunity
- Higher CE, better performance with respect to fatigue
- Highest yield in production of cells (less breakage)
- Multi-c-Si is limited in thickness reduction – cannot be wire sawed to same thinness
- Multi has reduced effective minority carrier lifetime

Recent reports have indicated the benefits of higher CE cells including better predictive output and having higher quality, less field failures, and lower degradation [7, 8]. Other reports indicate that improved harvesting results from the use of high CE mono-c-Si wafers. SunPower has reported a meta-analysis of 10 independent field tests of higher average kW-hr/kip production using higher CE cells [9]. These panels showed +5.3% higher harvesting levels compared with standard c-Si wafers, and +3.4% compared with thin film PV.

7 Kerf-free wafering: advantages

7.1 Improved metrics by kerf-free wafering

Significant cost reduction from implementing kerf-free wafering using mono-c-Si is possible. SiGen provides an approach that significantly improves utilization of mono-c-Si in a cost effective way. SiGen utilizes an implant-cleave cyclic process step to fabricate wafers and has demonstrated wafer thicknesses ranging from 150um to 20um with no kerf-loss [10]. In addition, the SiGen kerf-free wafers exhibit additional wafer properties that further improve the functionality of mono-c-Si wafers. In the particular case of the SiGen wafers, there are advantages both upstream and downstream. Further, the SiGen approach enables increased use of mono-c-Si with the associated benefits of higher CE and lower production costs in the value chain:

- Better materials utilization of mono-c-Si: <2.5gm/W
- Better wafer electrical characteristics
- Better wafer mechanical characteristics
- Ability to go to much thinner wafers w/o breakage w/even better gm/W (<1.5gm/W)
- Potential ability for lower surface impurities and the ability to getter bulk impurities which can reduce carrier lifetime
-

8 DATA FROM KERF-FREE WAFERS

8.1 SiGen approach for improved mono wafers

Recent data confirms some of the key features of kerf-free wafer approach developed by SiGen. The data shows low wafer micro-crack density that can improve reliability in downstream manufacturing and in the field.

8.2 Improved mechanical properties of SiGen wafers

Figure 3 shows various SEM images of SiGen kerf-free wafers at a range of dimensions from 20um to 150um.

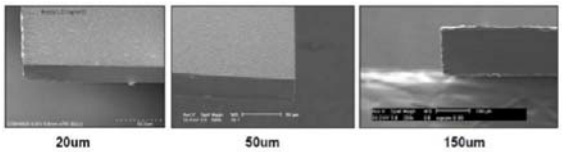

Figure 3. SEM images of various SiGen mono wafer edges

The following SEM is a close-up of the wafer edge showing a high quality edge with a smooth profile.

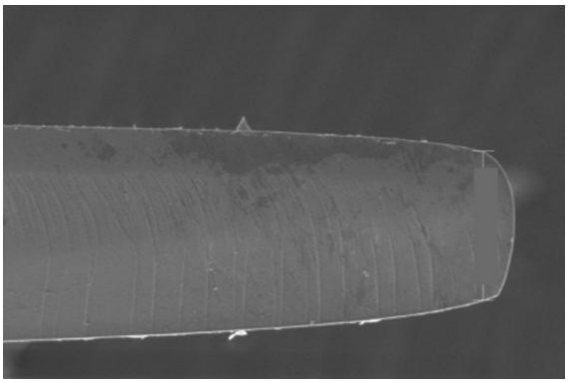

Figure 4. SEM image of the edge of a 60um SiGen wafer.

By comparison, wire sawn wafers exhibit micro-cracks that are intrinsic due to the use of an abrasive and saw process to produce the wafers. Substantial research has been done to attempt to reduce the count and size of micro-cracks. However, finer grit or slower cutting speeds typically used to lower the micro-crack density increase the overall costs in the wafering step. Even with these improvements micro-cracks are always present.

Another key feature of SiGen wafers is they have very low TTV so that the overall thickness does not vary across the wafers. This low TTV is particularly important for the cell manufacturing assembly and further demonstrates the robustness of these kerf-free wafers.

The significantly enhanced mechanical stability of the SiGen mono wafers would have which would improve the overall energy harvesting and consequently the Capacity Factor which improves the LCOE.

8.3 Enhanced electrical properties of the SiGen wafers

The kerf-free SiGen wafers also exhibit excellent electronic properties with regards to the carrier lifetime. The RF quasi-steady state photoconductance (QSSPC) setup using a Sinton WCT-120 was used to measure the effective excess minority-carrier lifetime of the wafers [11]. The generalized analysis was employed to correct the high lifetime data cases (<200μs), in which both generation and non-steady-state conditions take place [12]. Prior to the QSSPC measurements, all wafers underwent a lifetime recovery process. The process steps

were thoroughly discussed and effective lifetimes of over 250µs at 10^{15} cm^{-3} in a separate article [13].

Recent process modifications have yielded further lifetime improvements of both surface and bulk electronic properties of the PolyMax wafers with effective lifetimes of up to 470µs at $5{\cdot}10^{15}$ cm^{-3} (Fig. 5).

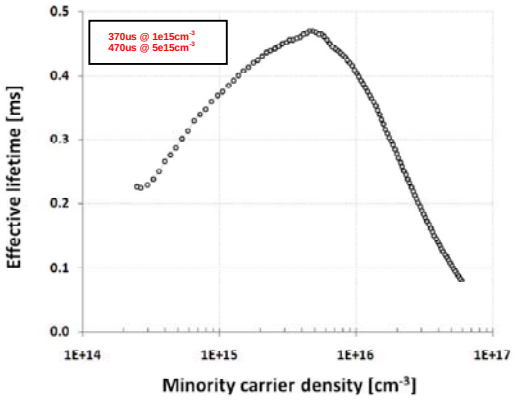

Figure 5. QSSPC effective lifetime measurements on Cz-Si (111) 100µm PolyMax wafers reported using the generalized analysis at $1{\cdot}10^{15}$ and $5{\cdot}10^{15}$ cm^{-3} minority-carrier densities, which correspond to ~0.3 and 1 Suns illumination levels respectively.

9 ADDITIONAL TECHNOLOGY ROADMAP CONSIDERATIONS

9.1 Diamond Wire for thin wafers

There is increasing activity with regards to Diamond Wire (DW) since at first glance this approach promises to provide a path to thinner wafers (around 100um) at modestly lower production costs [14]. However, there are various issues to consider. First, micro-cracks will still be present with the DW approach. Although there may be reductions in overall counts, breakage will likely remain. Second, there are early indications that DW will be most effective with mono-c-Si. Third, DW also can introduce surface variations which need to be accommodated during the cell processing steps.

The analysis of the DW development path is centered on its purported ability to fabricate thinner wafers and expand mono-c-Si. However, the ability of DW to enable wafers of 100um and below remains open because of micro-crack breakage and yield.

Cost analysis can be performed on Diamond Wire saw approaches using representative numbers from the current trending values. The results presented in the table below show that the kerf-free wafering process has significant cost and technical advantages. The cost modeling shows the kerf-free approach gave better $/W over wafer sawing approaches. The benefits further improve as the wafers get thinner. The micro-crack free wafers would also translate to downstream benefits.

Table 2a and 2b showing cost modeling comparisons

1st Gen PolyMax vs WS

Assumptions:			
Poly Cost per Kg	$50		
Ingot Conversion per Kg	$35		
CE%	18.0%		
Wafer Per Hour	400wph	185wph	185wph
Wire&Slurry/Wafer	$0.45	n/a	n/a
	WS	PolyMax	
	180um	150um	120um
g/Wp	6.00	2.20	1.76
$/Wp	$0.30	$0.11	$0.09
Ingot ($/Wp)	$0.21	$0.08	$0.06
Wafer ($/Wp)	$0.20	$0.25	$0.24
Wafer Cost/Wp ($/Wp)	$0.71	$0.44	$0.39
Total Cost per Wafer	$3.10	$1.91	$1.71
Cost Reduction (%)		38%	45%
Cell/Wp	0.15		
Module/Wp	0.2		
Total Cost of Module/Wp	$1.06	$0.79	$0.74
		26%	30%

2nd Gen PolyMax vs DWS

Assumptions:			
Poly Cost per Kg	$35		
Ingot Conversion per Kg	$30		
CE%	18.0%		
Wafer Per Hour	600wph	250wph	250wph
Wire&Slurry/Wafer	$0.30	n/a	n/a
	DWS	PolyMax	
	120um	120um	80um
g/Wp	4.00	1.76	1.17
$/Wp	$0.14	$0.06	$0.04
Ingot ($/Wp)	$0.12	$0.05	$0.04
Wafer ($/Wp)	$0.16	$0.18	$0.18
Wafer Cost/Wp ($/Wp)	$0.42	$0.30	$0.25
Total Cost per Wafer	$1.82	$1.31	$1.11
Cost Reduction (%)		28%	39%
Cell/Wp	0.15		
Module/Wp	0.2		
Total Cost of Module/Wp	$0.77	$0.65	$0.60
		15%	21%

9.2 Migration to n-type wafers

There is increasing interest in the use of n-type materials because of the numerous advantages presented. Some of these advantages are immediately relevant due to its higher CE and stability potential.

The advantages are outlined in Table 3.

Advantages	Effect	Reasons
Lack of B-O pairs in n-type Si bulk	Much less Light induced degradation	Dopant in n-type Si is P, not B
Positive minority carriers, less recombination at metal impurities	Higher efficiency more than P-Si solar cells	Metal impurities in Si usually neutral or positively charged
Better performance at weak light	Higher annual yield of n-Si modules	Smaller capture x-section for hole

Table 3: Advantages of n-type c-Si

Although multi will likely parallel development of n-type, the benefits are likely to be most pronounced with the mono materials. Again, this is a further driver for increased mono development and ultimately for increased mono adoption into the market.

The current activities on n-type PV are shown in Table 4.

Research institute	Substrate	Cell size (mm2)	Cell structure	Efficiency in Lab	Mass production	Average eff. in production
Sanyo	CZ	100x100	HIT	23.00%	Yes	~21%
Sunpower	CZAFZ	125x125	IBC	24.20%	Yes	~22%
Yingli +ECN+Amtech	CZ	156x156	Standard	19.89%	Yes	18.80%
UNSW	FZ	20x20	PERT	22.70%	No	-
Fraunhofer ISE	FZ	20x20	PERL	23.20%	No	-
	FZ	125x125	Ag-plated cont	19.30%	No	-
	CZ	125x125	Ag-plated cont	18.50%	No	-
International solar energy researcher center	CZ	156x156	SP	18.60%	No	-
University of Konstanz	CZ	125x125	SP	18.70%	No	-

HIT: Heterojunction with intrinsic thin-layer
IBC: Interdigitated back contct
PERT: Passivated emitter, rear totally-diffused
PERL: Passivated emitter, rear locaiy-diffused

Table 4. Current n-type Si activities

10 CONCLUSION AND SUMMARY

The primary historical metrics for the solar value chain has been the $/W cost. For the case of multi-c-Si in the panel, the costs have been lower compared to the reduction in CE and thus multi-c-Si presented an attractive cost-performance approach. However, the developing metric is the LCOE or Levelized Cost of Electricity that adds a wide range of additional elements into a cost-performance analysis. In an LCOE analysis, the full value chain beyond the module that includes the remaining Balance of System (BOS) with its fixed and variable costs. This metric is being further recognized by numerous funding agencies as a legitimate calculator for energy return.

The c-Si value chain has evolved from a poly-to-panel segment, to a poly-to-system chain, and is now entering into a new phase of a poly-to-electricity chain. Although the panels may become commoditized, their functionality plays an important role to affect costs throughout the broader chain. The performance of the panels and the cells are critical to the overall delivery of electricity due to their impact on the energy harvesting metrics. The discussion of overall energy production has acquired an even greater immediacy given the accelerating drive to reduce and eliminate Feed-in-tariffs (FIT's). Given that overall solar installations must now produce competitive rates for electricity, it is necessary to examine the full value chain and how the poly-to-electricity LCOE can be improved.

The mono wafers are positioned to provide the necessary characteristics for this drive. Innovative approaches such as that provided by kerf-free wafering of mono wafers which give even better mechanical stability, increase the value of the mono wafers and further enable the LCOE cost reduction to help establish solar at grid parity without subsidies.

11. ACKNOWLEDGEMENTS

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