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Lifetime in the Field: Technology Transfer, Manufacturing and Field Performance of CSG Solar Modules

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Abstract
The transition for solar cell device research to manufacturing and deployment presents significant challenges and opportunities, whether the target is to replace or improve an existing process, or to disrupt with a new technology. This paper reviews some of the challenges, outcomes and lessons learnt in the commercialisation of the Australian thin film Crystalline Silicon on Glass Technology (1995-2010). Included, for the first time, are field results from CSG Solar modules after over 12 years field deployment (2007-2020), compared to predictions from accelerated lifetime testing completed 1997-2007.

Introduction
The CSG Solar technology was developed in Australia between 1994 and 2005 by Pacific Solar Pty Ltd [Green, 2008] and taken into manufacturing in Germany by CSG Solar AG, between 2005 and 2010. While manufacturing was halted in 2010, research is ongoing at HZB, Berlin where they continue to improve on the technology, achieving cell efficiencies of 15% [Garud 2020] targeting process improvements to increase efficiency and reduce price [Chang 2015].

The crystalline silicon on glass technology promised to address the difficulty that silicon wafer-based technology was expected to face in reaching very low costs as well as the perceived fundamental difficulties with other thin-film technologies. The aim was to combine the advantages of standard silicon wafer-based technology (durability, good electronic properties and environmental stability) with the advantages of thin-films, specifically low material use and large-scale, monolithic processing.

Investment was secured to take this Australian technology into manufacturing in 2005 when there was a spike in interest in thin film solar technologies, due to the perceived risk that the supply of silicon wafers would not be sufficient to meet the expected demands of solar module manufacturing. At that time, silicon was predominantly sourced from waste material from integrated circuit manufacturing.

Durability Testing for Early Stage Innovation
Core to securing investment in a disruptive technology, is balancing the risk and opportunity of innovation with ongoing market and technology development in the incumbent technology. As well as demonstrating competitive mini-module efficiencies (then 10%) and record efficiencies over 12%, it was key to demonstrate longevity of the emerging technology. Silicon wafer based modules had 15-20 year warranties then – and are now extending out to 40 years.

As significant field data for the developing technology was not available, internal product testing was developed to simulate accelerated module degradation, including damp heat, thermal cycling, and humidity freeze. At the time, the standards did not require the same module to undergo the variety of simulated, real-life environmental conditions. Each test was performed on a fresh module. At Pacific Solar, an extended sequence of the IEC 61215 standard was developed, described as Combined Cycle testing, as a more comprehensive way to simulate the impacts of real-life, long-term environmental stressors [Luechinger 2008].

Using this novel Combined Cycle Testing, emerging technologies can be compared against the standard technology, determining durability in a time frame consistent with the months of manufacturing process development rather than years of field deployment. Using this methodology, CSG solar technologies were developed to exceed two combined cycles; being compatible with Tier 1 mono-crystalline technologies and better than Tier 2 polycrystalline technologies (as shown in Figure 1).

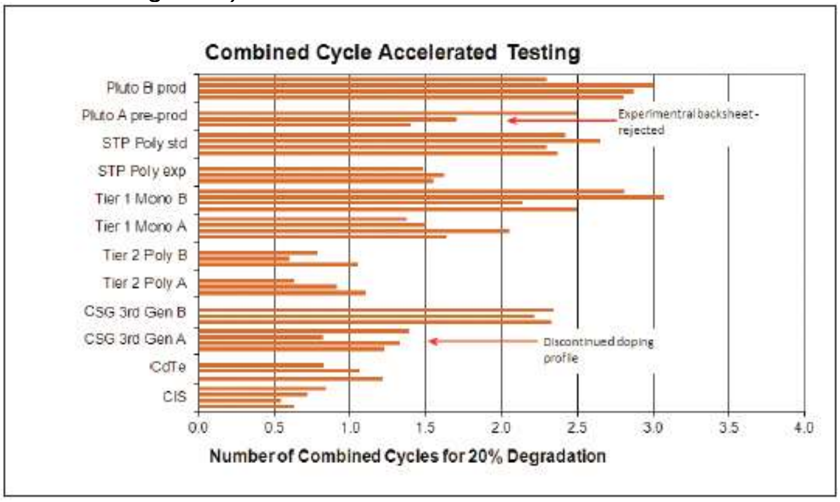


Figure 1. Combined Cycle Test Results, Jarnason 2012

Technology Development and Manufacturing

In this work we compare the field data to the simulated test results against a range of real-world performance data, validating the combined cycle testing methodology. Real world deployments of the CSG Solar Technology produced on the Sydney Pilot Line prior to 2005 are shown in Figure 2. While in Figure 3, are images of the CSG Solar Manufacturing Facility, in Thalheim Germany and field deployment, also in Germany in 2007.

Figure 2. Early field prototypes for lifetime testing, Pilot Line Roof (Left), Power House Museum, Sydney (Right), 2007.

Figure 3. Large Scale Manufacturing (Left) and Deployment (Right) (2005-2010)

Field Performance

Presented here for the first time are field performance data from over 12 years of continuous operation and monitoring. Modules were installed in Sydney in October 2007, on a residential rooftop and in less than ideal conditions. The roof is oriented east-of-north and suffers from winter shading. The system was monitored, initially with a combination of the SMA Sunny Webbox automatic recordings and manual records. Manual records were maintained because the automatic monitoring failed due to connectivity issues. From late 2015, the system has been monitored using Solar Analytics – providing more detailed insights into performance against expectation.

In Figure 4, the total monthly generation is shown or the years 2007 to 2020. Performance variations due to weather dominate any longer term effects and more detailed analysis is needed to determine if there are module degradation effects.

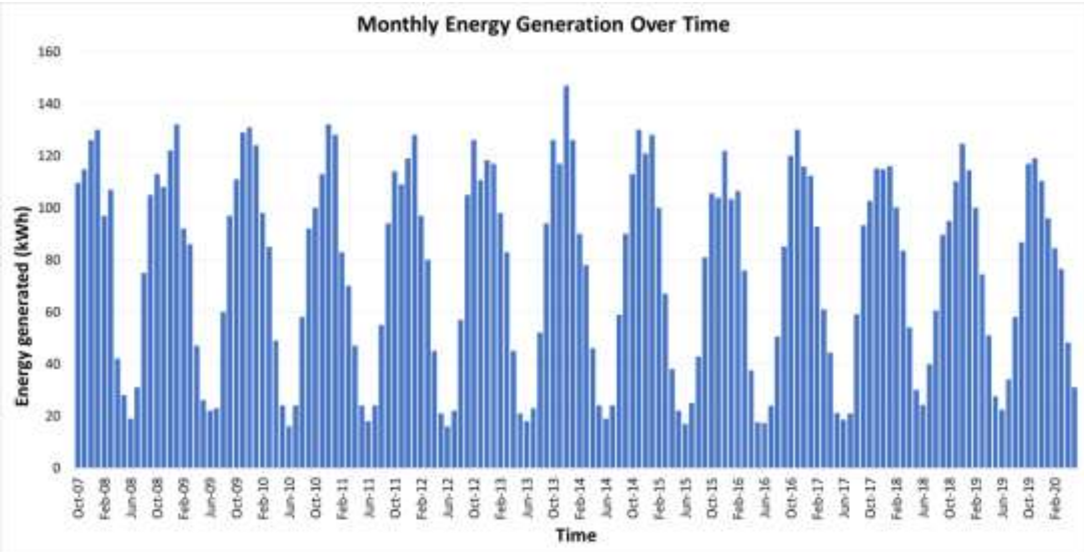
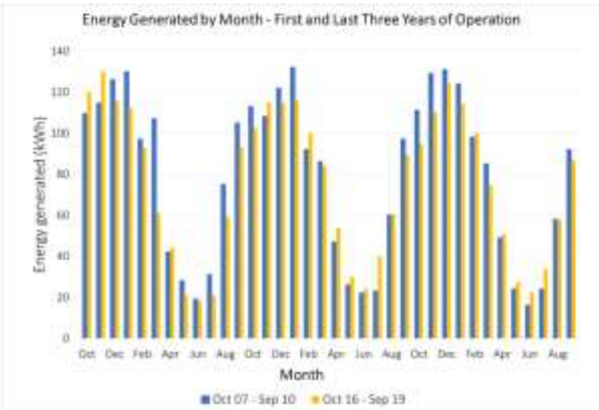


Figure 4. Field Performance, Monthly Energy Generated, 2007-2020

In Figure 5, the total monthly generation is shown for the first three years 2007 to 2010 (blue) and the last three years 2016 to 2019 (yellow). In Figure 6, the total monthly generation is shown for the period 2007-2020 for the months of December and June.



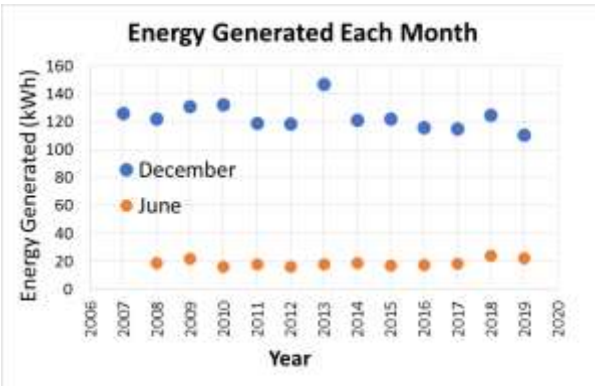


Figure 5. Monthly Energy Generated. First and last three years.

Figure 6. Monthly Energy Generated over 12 Years, December and June.

The module performance is not showing any detectable degradation over time. The significant difference between the December and June performance is due to winter shading in June. This can be seen clearly in the performance against expectation shown in the Solar Analytics monitoring [Solar Analytics 2020]– where the summer performance is at least as good as expected for the system size and orientation, while the system consistently under-performs in winter.

Figure 7. Solar Analytics Monitoring. Data collection, information and alerts

Epilogue

In 2005, when the investment was made in scaling up the CSG Solar technology, silicon cell and wafer technology was an emerging industry; a large module manufacturing line was 100MW, module prices were $8/Wp and Australia installed only 8.2MW in the year, for a total installed capacity of 60.6 MW, where only 7MW was grid connected. The industry was changing rapidly. Data in Table 1, taken from IEA reports and from Mints, 2020, shows the rapid drop in module and system price and the rapid escalation in installations and manufacturing capacity.

Table I. Changing PV markets [IEA PVPS Reports 2005,2010,2015,2020 and Mints, 2020]

	Average Module Pricing AUD/Wp	System Pricing AUD/Wp	Annual Installs (Australia) MW	Total Installed Capacity (Australia) MW	Total Installed Capacity (Global) GW	Manufacturing Capacity (Australia) MW	Manufacturing Capacity (Global) GW
2005	8	12	8.2	60.6	3.7	10	2.5
2010	3.20	6.0	383	571	20.4	12	7.1
2015	0.80	2.45	992	5,109	177	60	46.7
2020	0.52	1.60	4,750	16,300	627	60	153

While some price competition was expected, the more-than-halving of module costs between 2005 and 2010 exceeded all expectations. In 2010, with around 20 MW of CSG modules produced and modules fielded in residential rooftop, commercial and industrial and utility scale arrays, manufacturing was stopped and resources shifted. For the Australian team, manufacturing effort shifted to focus on the lower-cost silicon wafer based technology, while research into crystalline silicon on glass technology continued, looking at more cost effective materials preparation processes and increased efficiency.

The presentation will include more detail on performance, further insights into the benefits of accelerated lifetime testing and lessons learnt over a lifetime in the field.

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