QUANTIFYING PV LOSSES FROM EQUIVALENT CIRCUIT MODELS, CELLS, MODULES AND ARRAYS

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ABSTRACT: Analysis of photovoltaic cells is often performed with 1-dimensional device physics models and 2-diode equivalent circuit fitting to light and dark IV curves. These find that the theoretical cell area efficiency limits for single junction Si PV cells are around 30% due to the inability to collect photons with energy below the band gap and wasted energy for photons above the band gap. The best commercial scale modules have dc cell area efficiencies in the 14 to 15% range for multi Crystalline Si and in the 16 to 20% range for mono crystalline Si. The AC Module area efficiency of c-Si arrays in the field will usually be at best 10-12%. This paper studies the origin and magnitudes of losses. It shows which factors are most important to the performance of an array in terms of efficiency and kWh output.
Keywords: Modelling, Monitoring, Performance

1 INTRODUCTION

Multi and Mono crystalline Si are the dominant photovoltaic production technologies in terms of kWp/year at 56.3% and 33.2% respectively for 2003 with just 4.5% (falling with time) for a-Si [1]. Efficiencies of production screen print multicrystalline are presently limited to below 15% by the substrate material quality, shading, contact resistance, recombination and heavy emitter doping.

Laser Groove Buried Contact Cells (BP Solar's Saturn) are made using better quality monocrystalline silicon (with higher bulk lifetime than multi) and because of their selective emitter doping, lower reflection, lower shading losses and better contact resistance have efficiencies above 17% (pilot line cells had an efficiency of 18.3% for 147cm² cells [2])

2 PHYSICAL AND ELECTRICAL DIFFERENCES BETWEEN TYPICAL SCREEN PRINT MULTI CRYSTALLINE AND LGBC MONO SOLAR CELLS

Figure 1 shows a Cross section of a Laser Grooved Buried Contact Cell showing pyramidal texturing and Grid lines plated into the grooves (as opposed to a screen print device where the grid lines are printed onto the surface of a cell.

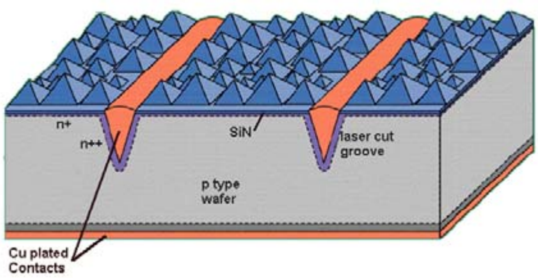

Figure 1: Schematic cross section through a LGBC Saturn cell

Table 1 details some of the main differences between typical screen print mc-Si cells with BP Solar's new 7 series Saturn (first produced in April 2004).

Note that historically most Module suppliers have sold with measured module powers in a range down to a few percent below the nameplate rating, whereas the new Saturn 7 range are "**REAL POWER**" [3] i.e. the measured STC test Pmax Wp is equal to or above the nameplate rating).

TABLE 1: Some Physical and Electrical Characteristics of a typical mc-Si screen print against Saturn 7 series

	Typical mc Screen Print	**Saturn 7 LGBC**
Typical Cell Area cm²	~156 to 225	~ 150
Shape	square	Pseudo-square
Typical Cell Efficiency	~14.5 %	17.5%+
Power Rating (Actual STC Wp / Nominal Wp band)	Typically -5% to 0%	**0 to +2.5% (Real Power [3])**

3 EQUIVALENT CIRCUITS

Figures 2 and 3 show equivalent circuits superimposed on not-to-scale cross-sections of typical multicrystalline screen print and LGBC cells (they are intended to identify where in the physical cell the equivalent circuit elements come from.) Note that multicrystalline wafers may have shunt paths and series resistance paths across grain boundaries.

For LGBC cells the laser is used to cut grooves in the Si 35um deep and just 25 um wide, much narrower than screen print fingers (for lower shading losses). Plating is used to fill the grooves to make a much larger cross sectional area of metal to ensure a lower metallisation resistance.

LGBC cells also have selective emitters enabling low resistivities under the fingers (10 ohms/[]) for low contact resistance and lower doping densities on the emitter (100 ohms/[]) for good light capture, (see the higher internal quantum efficiency Figure 4).

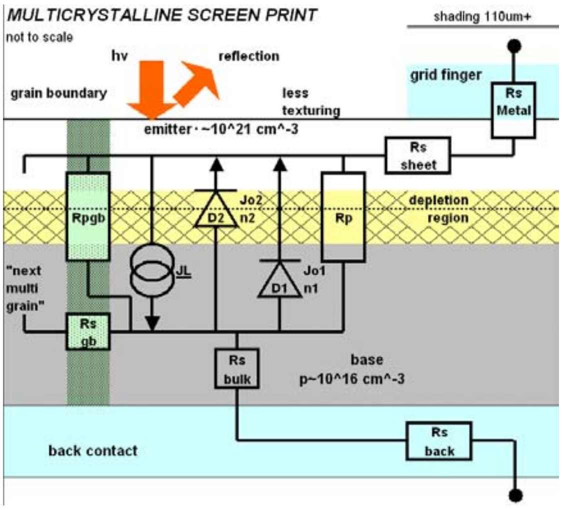

Figure 2: Equivalent Circuit and Cross Section of a Standard Multi Crystalline Screen print Cell

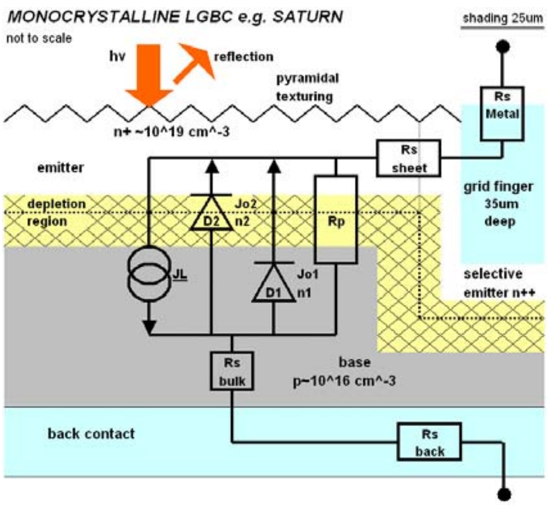

Figure 3: Equivalent Circuit and Cross Section of a Laser Grooved Buried Contact Cell (Saturn)

Figure 4 illustrates that the IQE of the LGBC is better than the Multicrystalline up to 1100nm, particularly near the blue end of the spectrum due to its better reflectivity, surface and optimised selective emitter contact.

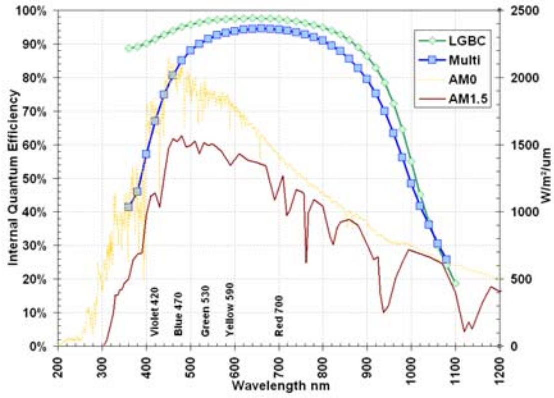

Figure 4: Internal Quantum Efficiency for typical Multicrystalline and LGBC Saturn with Standard Spectra for AM0 and AM1.5G vs wavelength

Table 2 lists some of the material and device parameters for a Typical screen print mc-Si cell as compared with Saturn 7 cells,

TABLE 2 : Material and device Parameters

	Typical mc Screen Print	**Saturn 7 LGBC**
Front Surface Texturing	Poorer or no texturing as random oriented grains	Pyramidal Texture ~ 5um
Emitter doping cm^{-3} n-type	Uniform $\sim 1*10^{21}$	Selective $1*10^{19}$
Emitter Sheet resistivity Ω/[]	40 to 50	100
Bulk Lifetime µS	1-5	15
R Series Ω	$7\text{-}8*10^{-3}$	$5*10^{-3}$

4 LOSSES AT EACH STAGE

Figure 5 shows the losses making the DC efficiency of a cell lower than the intrinsic efficiency. Approximately 71% of incident irradiation has energy below the band gap of a Si cell or is wasted energy above the band gap. The effect of reflectance, shading by grid fingers and bus bars, recombination, I^2R loss in the series resistance are shown and result in typical efficiencies of 14.5 and 17.5% for Multi crystalline screen print and Saturn 7 respectively.

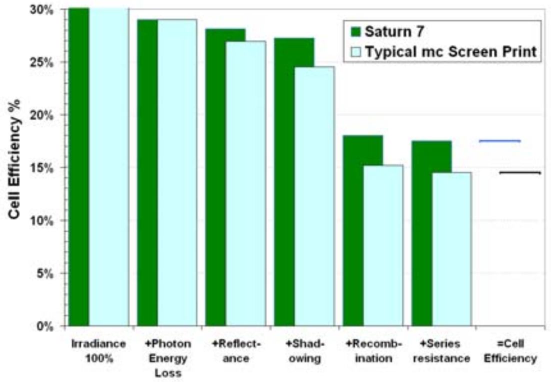

Figure 5: Losses involved in determing the efficiency for typical multicrystalline screen print and Saturn 7 cells.

Figure 6 shows typical losses from the cell to module assembly. These losses are similar for the module types except for the packing density which is better for square or rectangular multi wafers than the pseudo square mono.

Saturn 7 cells are cut pseudo square from larger diameter boules compared with other pseudo square modules resulting in very good packing densities which helps keep the module efficiency high.

Losses shown are Encapsulation and glass loss, Cell Tabbing Resistance, Cell mismatch and packing Density.

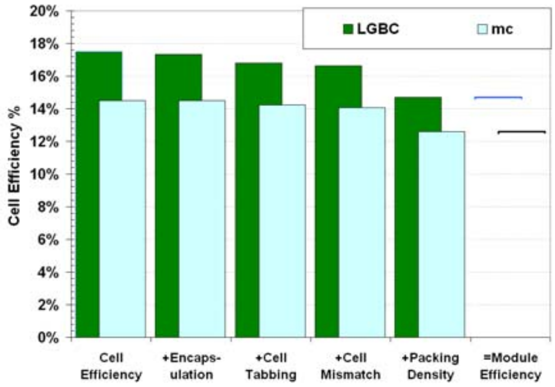

Figure 6: Losses involved in determing the efficiency for typical multicrystalline screen print and Saturn 7 modules cells.

6 MEASURED DC MODULE EFFICIENCIES UNDER REAL WEATHER CONDITIONS

The efficiency of LGBC modules will be higher than mc-Si at all light levels and temperatures. Figures 7 and 8 show the average measured dc module efficiencies of a typical competitor's mc-Si module and a Saturn 7 LGBC measured at BP Solar's outdoor test facility in Australia.

The Saturn 7 is 2% absolute higher efficiency (approximately 13-14% rather than 11-12% module efficiency) over all real measured conditions.

Note that at one sun the Tambient was mostly 20-30C and the Tmodule was usually 50-60C.

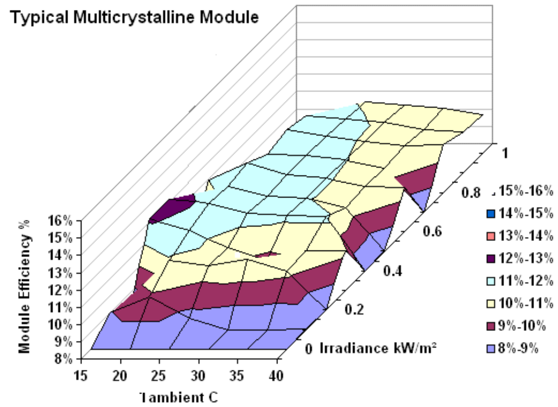

Figure 7: dc Module Efficiency versus Irradiance and $T_{AMBIENT}$ for a typical competitor's multicrystalline module measured in Australia with a swept IV data logger

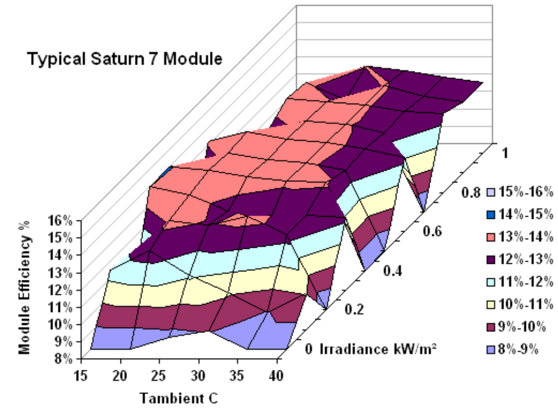

Figure 8: dc Module Efficiency versus Irradiance and $T_{AMBIENT}$ for a typical Saturn 7 module measured in Australia with a swept IV data logger.

7 EXTERNAL SYSTEM LOSSES

External losses depend to a large extent on the type of system and can vary widely (particularly losses due to dirt, shadow and ambient temperature)

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The following lists some of the loss mechanisms with some comments.

- Thermal effects (c-Si will fall ~ –0.45%/deg C Tmodule, the effect depends on mounting arrangement and Tambient)
- Dirt - Depends on rainfall and frequency, often <4%
- Snow - Linear fall with snow depth to 10cm
- Stability - Usually good for c-Si
- Angle of Incidence - Usually low loss below 60°
- Spectral changes - Low for single junction

- Wind - (depends on mounting arrangement)
  Reduces Tmod ~3 °C/(ms^{-1}),

- Vmax Tracking inaccuracy -
  Slightly worse for high FF devices.
  Depends on BOS component quality

- MPPT parasitic losses

- Dc wiring - Should be low <2%

- Inverter efficiency - Usually >92% efficient, drops at low light levels

- AC wiring losses - Should be low <2%

- Shadow (worst in winter ?) - Dependent on module topology and obstacles,

- String Mismatch - (Worst modules dominate) - String equivalent modules where possible (e.g bottom row more prone to shading)

- Downtime - Worse loss in Summer, depends on expected time to repair.

Correct sizing and selection of quality of BOS components and wire sizing may minimise many of the electrical losses.

Figure 9 shows graphically the change in performance due to each loss stage and the likely variation between best and worst performing sites due to Module characteristics, Site conditions, mounting and BOS Performance.

The left hand side of the graph has a Performance Ratio of 100%; this is what would be expected from a dc Module with its Pmax equal to the nameplate rating and no losses.

Losses are then added in turn, showing the best (top) and worst (bottom) drops in performance to be expected from each stage.

The black line shows the values from a typical monitored array on the East Coast of the USA.

The measured losses gave it an expected Performance Ratio of 76%.

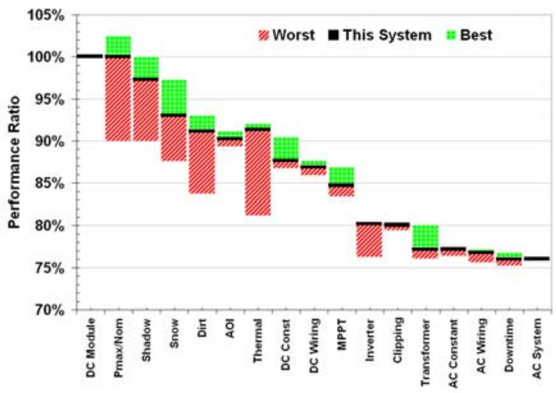

Figure 9: Range of expected performance losses due to 16 different effects. 100% (left) corresponds to the dc Nominal Module dc efficiency; the right hand value (here 76%) corresponds to the final Performance Ratio.

8 CONCLUSIONS

- Multicrystalline and Saturn 7 cells have been modelled and loss mechanisms estimated for the cell efficiencies.
- Losses have been listed and ranges given in going from dc module efficiency to ac system efficiency

- BP Solar's Saturn 7 series modules are sold with REAL POWER ratings meaning that the tested Pmax rating is at or above the nameplate, giving better value to customers than almost all competitors who sell modules below the nameplate reading. This translates into a better kWh/kWp as the value depends on the actual Wp/nameplate ratio.

9 REFERENCES

[1] Photon International March 2004 p53
[2] Bruton et al, WCPEC-3, Osaka 2003 http://www.bpsolar.com/ContentDocuments/154/4pl-e1-01.pdf
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