ON-SUN PERFORMANCE OF A NOVEL MICROCELL BASED HCPV SYSTEM BASED IN TUSCON AND COMPARISON WITH CONVENTIONAL SYSTEMS

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ABSTRACT

On sun performance data for a 1 kW HCPV RD&D system is presented. The HCPV modules are fabricated with transfer printed micro-cells that operate at a concentration of 1000 suns. This system, installed in Tucson, AZ, is the first field validation of this novel approach that addresses the cost, performance and reliability aspects of HCPV systems. The performance of the Semprius HCPV system is compared with that of alternative PV systems, also being tested at the same location. Finally, current developments on Semprius' technical roadmap are described.

INTRODUCTION

Semprius has developed a novel microcell based, highly scalable HCPV module that addresses performance, cost and reliability requirements for utility scale solar installations [1]. This prototype module has a geometric concentration ratio of 1000 suns and III-V based dual junction 0.36 mm^2 microcells that are transfer printed in a massively parallel fashion. New Semprius printed 3J cells have an efficiency of >40%% under 1000 suns. The 14"x14" module has 324 receivers attached to a metal backplane through a standard SMT process. The module has a silicone on glass primary lens and glass secondary lenses. Micro-cells have a number of significant benefits; they enable two-stage refractive optics with a short optical path, and distributed heat dissipation through the backplane for passive heat transfer with no additional heat sinks required. Transfer printing also enables GaAs substrate re-use, and a highly scalable manufacturing process to further reduce cost. These attributes improve performance, reduce cost, and improve reliability. A RD&D system consisting of 48 such prototype modules on a 2-axis tracker was installed at Tucson Electric Power (TEP) in Tucson, AZ in August, 2010 [2]. This paper will present the first ten months of on-sun results from the system. The results will be compared with conventional systems, also being tested at the same location. The conventional systems include mono and poly crystalline silicon and thin film silicon. Finally, recent developments of this technology will be presented.

SYSTEM DESCRIPTION

Figure 1 presents the Semprius system consisting of 48 engineering prototype modules on a 2-axis tracker, connected to an inverter and a data acquisition system. The 2-axis tracker was provided by Siemens, and uses Siemens' Simatic S7-1200 automation with NREL's Solar Positioning Algorithm (SPA) and provides a tracking accuracy of better than ±0.1 degrees. Figure 2 presents a picture of the TEP test yard with more than 20 systems under test. The technologies that were selected for comparison to HCPV were mono crystalline silicon (x-Si), polycrystalline silicon (p-Si), thin film silicon (TF-Si) and hetero-junction with intrinsic thin film silicon (HIT-Si). All systems were mounted at a tilt of 32 degrees.

Figure 1: Semprius RD&D system

Figure 2: TEP test yard

IRRADIANCE

Figure 3 presents the Direct Normal Irradiance (DNI), Global Normal Irradiance (GNI) and Global Horizontal Irradiance at 0 degrees (GHI) for a sunny day (August 19, 2010) in Tucson. The DNI is determined by an Eppley NIP mounted on the CPV tracker, and the GNI is determined using a Licor LI-200, also mounted on the tracker. The GHI is determined by a Middleton pyranometer, mounted on a horizontal surface. On a sunny day, such as August 19, 2010, the direct normal insolation was about 90% of the global normal insolation and the global horizontal insolation was 76.6% of the direct normal insolation. The average daily direct normal insolation at this site for the ten months was 6.6 kWh/m^2.

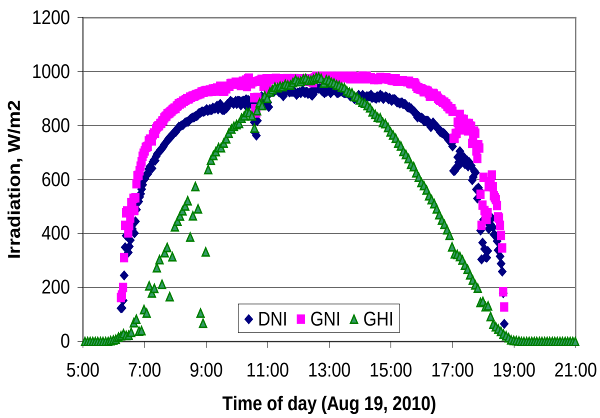

Figure 3: Irradiance profile at TEP on a sunny day

HCPV RESULTS

Figure 4 presents the tracker error over the course of a day. The tracking error of the Siemens tracker is within ± 0.1 degrees. The tracking accuracy was measured with a position sensing detector that was calibrated with a Green Mountain Trac Stat SL-1. The tracking error is well within the angle of acceptance of the modules, which is ±0.8 degrees.

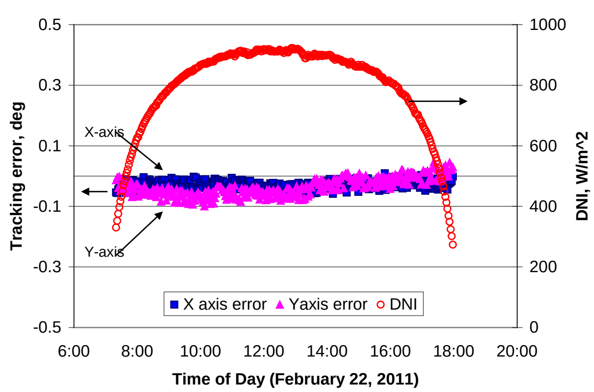

Figure 4: Tracking error for one day

Figure 5 presents plots of AC and DC power on typical sunny days in May and December, showing seasonal effects. The DC energy output on Dec 13, 2010 was 8.1 kWh, and on May 12, 2011 was 10.2 kWh. The inverter efficiency was 96%. The plot also highlights the benefit of two-axis tracking: relatively stable power output, for most of the day. HCPV on a two-axis tracker is a much better match for a utility's demand curve than un-tracked PV. The peak load for utilities is generally from 4 PM to 7 PM.

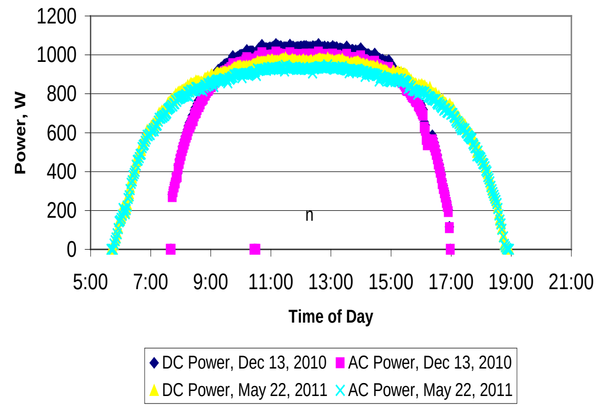

Figure 5: Effect of seasons on power

Figure 6 presents the cumulative energy yield in kWh$_{ac}$ per kW$_{dc}$ installed during the ten months of operation. Two of the primary goals of this field testing are validation of the technology and assessment of long term performance. The system has been in continuous operation since its installation on August 3, 2010, with few exceptions. There was an inverter error a few days after the installation, which was corrected by the vendor, and a tracker motor failure that resulted in the replacement of the motor in April 2011. In addition, the system was taken offline intermittently for engineering experiments, including several days in February, 2011

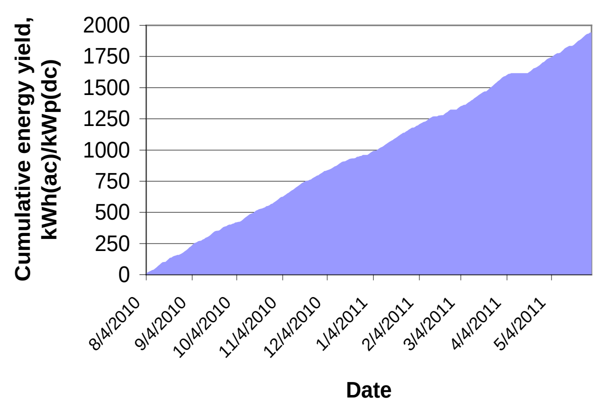

Figure 6: Cumulative energy yield in kWh (AC) per installed kW (DC).

Figure 7 presents the peak daily AC power per kW$_{dc}$ installed for the ten months of operation. It is observed that the system operates very close to the system rating. The disruptions in this plot are weather related or related to the issues discussed earlier.

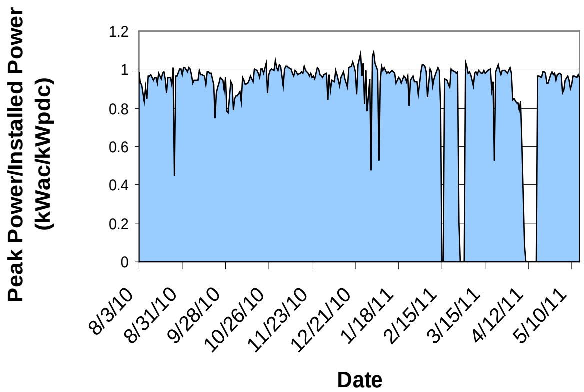

Figure 7: Ratio of daily peak AC power (kW) to installed DC power (kW).

Figure 8 presents the system daily annualized energy yield for the system (blue bars) along with monthly averages (black lines) for the ten month period from August, 2010 to May, 2011. The average annualized energy yield was about 2500 kWh/kW$_p$ for the ten months of operation. . Outages discussed earlier are omitted from the annualized energy yield and capacity factor measurements reported next.

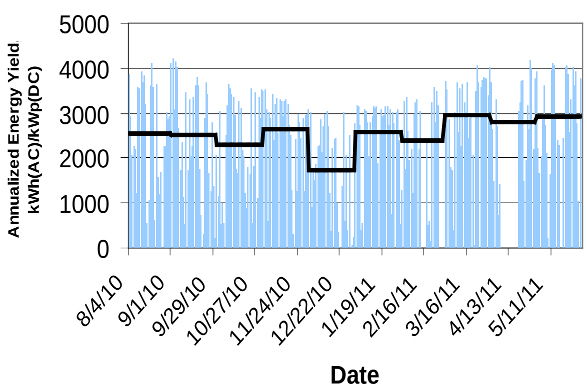

Figure 8: Energy yield, daily and monthly average

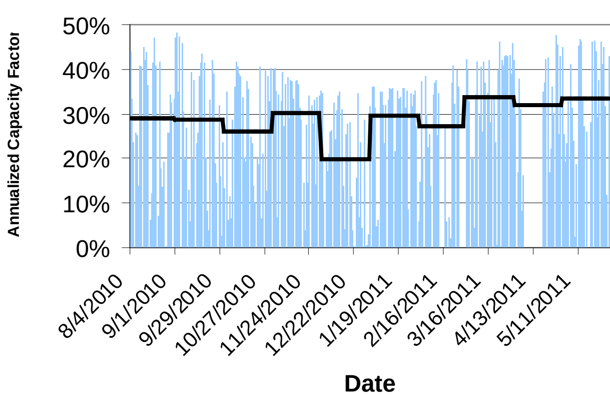

Figure 9: Capacity factor, daily and monthly average

Figure 9 presents daily capacity factor and monthly averages for the ten month period from August, 2010 to May, 2011. The monthly capacity factor ranges from a low of 20% in December to a high of 34% in March, and is expected to be higher in the upcoming summer months. The average capacity factor was about 29% for the ten months of operation.

Heat dissipation at high concentration is an important consideration in HCPV module design. Semprius addresses heat management by using micro-cells that distribute the heat over the entire backplane. The copper interconnects and the metal backplane then dissipate the heat to the environment. In this low-cost solution, no heat sinks, heat spreaders or forced circulation are used. The data from this RD&D system validates this approach. Figure 10 presents the thermal performance of the system on a hot, sunny day when the ambient temperature rose from 25°C in the morning to >40°C in the afternoon. The backplane temperature rose to a maximum of 60-65°C in the afternoon with an ambient to backplane temperature delta of 15-25°C, which is consistent with our FEA simulations and module testing results.

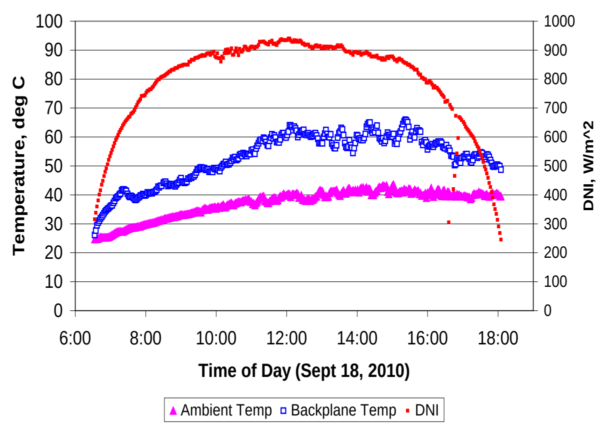

Figure 10: Thermal performance of HCPV system

TECHNOLOGY COMPARISON

The TEP test yard where the Semprius HCPV system is located has more than 20 other systems also under test [4-6], providing an opportunity to compare different technologies under the same weather conditions. The technologies that were selected for comparison to HCPV were mono crystalline silicon (x-Si), polycrystalline silicon (p-Si), thin film silicon (TF-Si) and hetero-junction with intrinsic thin film silicon (HIT-Si). All systems were mounted at a tilt of 32 degrees. Table 1 summarizes the specifications of the systems selected for this study. Table 2 summarizes the performance of the different technologies for a sunny day (Aug 19, 2010), a cloudy day (Nov 11, 2010) and for a three month period (Aug 22 – Nov 27, 2010).

Figure 11 presents the energy yield for all the systems on August 19, 2010, a sunny day. The energy yield of the Semprius HCPV system is almost two times that of the next highest system, TF-Si. The differences in energy yield are because of two-axis tracking, module rating method and temperature coefficients. Two-axis tracking systems capture a larger portion of the solar radiation than a non-tracking system. In addition it is noted that the ratio of peak power to rated power is >30% higher for the Semprius HCPV system than TF-Si. This is because flat plate systems are rated at a cell temperature of 25°C, but the actual cell temperature at typical operating conditions in Arizona is much higher than 25°C. The Semprius system is rated at an ambient temperature of 20°C. The temperature coefficient of the 2J III-V multi-junction solar cells (-0.17%/C) is also more than a factor of two lower than that for Si solar cells (-0.45%/C). The output of the HCPV system is particularly attractive during the summer afternoon peak load that occurs between 4 PM and 7 PM.

Figure 12 presents the performance of the systems on a partially cloudy day. Despite momentary losses in output power, the overall energy yield of the HCPV system is higher than the others, even on partially cloudy days. Cumulus clouds block nearly all the irradiance to both HCPV and to flat plate systems. However, flat plate PV performs better when shaded by high thin stratus clouds that only scatter light. The well known "edge of cloud" effect that causes a spike in power for flat plate systems can also be observed in Figure 12 [3]. The HCPV system displays no such effect. Figure 13 presents the daily average energy yield of the systems from August 22 to November 27, 2010. The average energy yield for this period is about 50% higher for the HCPV system than the next best performing system.

Table 1: PV system specifications at test yard

System	Technology	Rating, Wp_{dc}	Rated efficiency	Measured efficiency	Inverter efficiency	Rating Condition
Semprius	HCPV	929	21.6%	17.5%	96.0%	PTC
Sunpower, SPR 215	x-Si	1935	17.2%	13.9%	96.6%	STC
Sharp, NE-QE2U	p-Si	2970	14.1%	9.8%	94.0%	STC
Unisolar 64	TF-Si	1536	6.9%	5.7%	95.2%	STC
Sanyo, HIP-J54BA2	HIT-Si	1440	17.0%	11.3%	93.0%	STC

PTC – PVUSA test conditions, 850 W/m^2 DNI, 20°C ambient temperature
STC – Standard test conditions, 1000 W/m^2 GHI, 25°C cell temperature
Measured efficiency (AC energy produced/Insolation) is for Aug 22 – Nov 27, 2010

Table 2: PV system performance results

System	Technology	Peak Power/Wp (kW_{ac}/kWp)	Energy Yield (kWh_{ac}/kWp/day)	Energy Yield (kWh_{ac}/kWp/day)	Energy Yield (kWh_{ac}/kWp/day)
Test Period	-	Aug 19, 2010	Aug 19, 2010	Nov 11, 2010	Aug 22-Nov 27, 2010
Semprius	HCPV	1.09	11.2	6.9	7.3
SunPower	x-Si	0.75	5.43	4.96	4.9
Sharp	p-Si	0.63	4.74	-	3.9
Unisolar	TF-Si	0.80	5.81	-	4.9
Sanyo, #12	HIT-Si	0.61	4.45	3.75	4.0

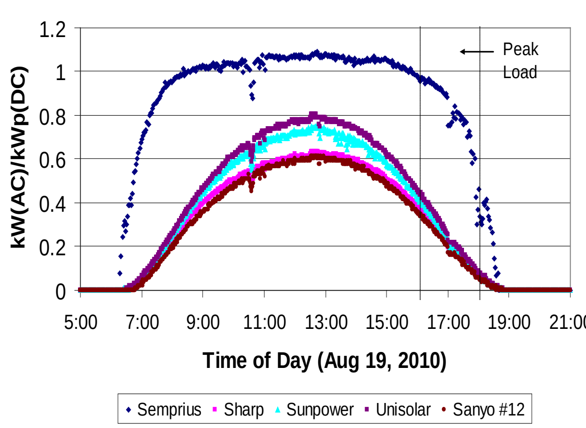

Figure 11: Energy yield on a sunny day

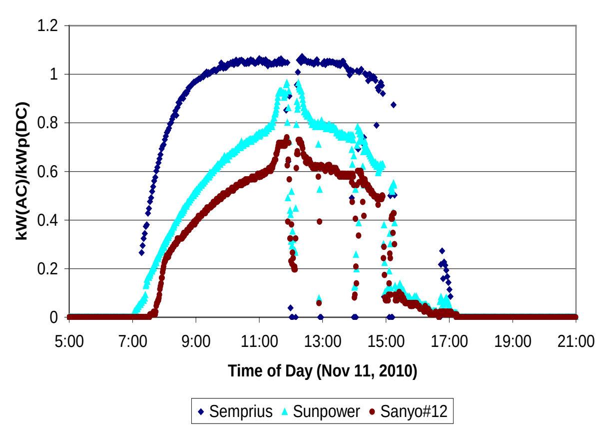

Figure 12: Energy yield on a partially cloudy day

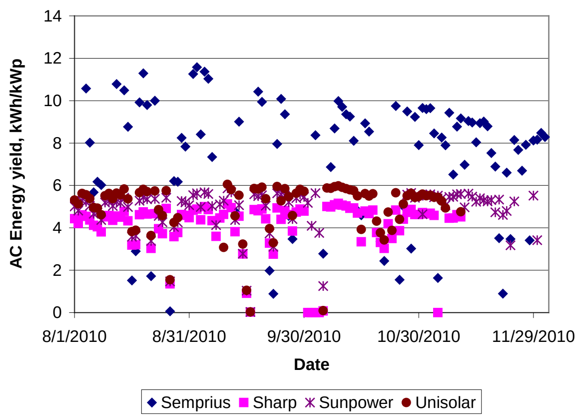

Figure 13: Energy yield for Aug-Nov, 2010

Figure 14 presents the thermal performance of three technologies (HCPV, TF-Si and p-Si) on a hot day, along with ambient temperature. It is observed that the V_{mp} of the III-V based HCPV system remains relatively unchanged with temperature. In contrast, the V_{mp} of the p-Si system and the TF-Si system decreases around mid-day due to their higher temperature coefficient. The V_{mp} of the Si systems increase later in the day because they perform better at higher air mass (red rich), which matches their bandgap.

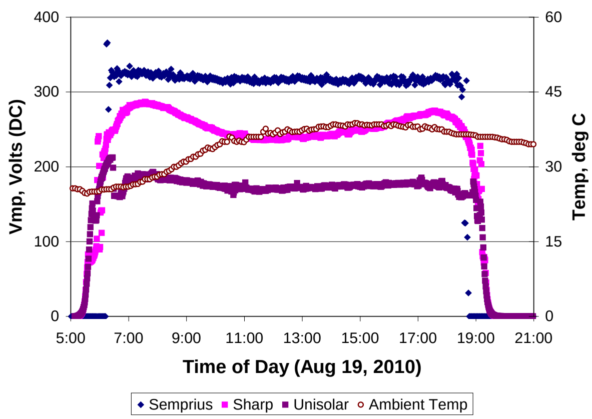

Figure 14: Thermal performance on a sunny day

PERFORMANCE MODEL

The ability to predict energy generation is very important to the bankability of a system. A performance model, developed at the University of Arizona, uses a solar position algorithm to predict irradiance incident on HCPV and flat plate systems every minute of the year, combined with cloudiness indexes for Tucson derived from PV system outputs. This model incorporates measured conversion efficiencies presented here, and historical yields measured for flat plate systems and the Semprius HCPV system. Figure 15 presents the prediction from this model and data (from different years) for verification. These predictions suggest that the expected energy yield of the HCPV system is 1.3 to 1.7 times the typical yield for flat plate systems in the same yard. The range in this prediction is mostly due to the varied performance of different flat plate systems. HCPV yields are higher due to tracking and module rating methodology (as indicated by the solid curves in Figure 15 that show predictions for sunny days). However, HCPV yields are affected differently than flat plate systems by clouds and aerosols, temperature effects, and soiling (as indicated by the dotted curves in Figure 15 that show predictions normalized by the annual average reduction in output due to clouds for each system). The models predict that the annual energy yield will be 2580 kW_{ac}/kWp_{dc} for the Semprius RD&D system at TEP.

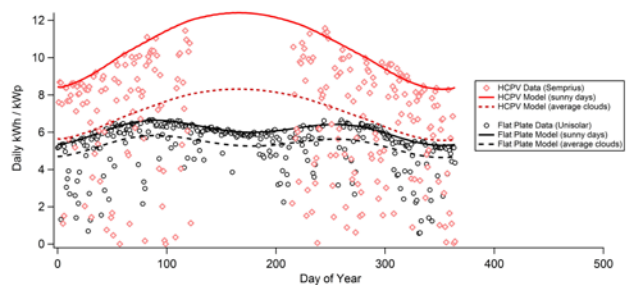

Figure 15: Performance model

CURRENT DEVELOPMENTS

The RD&D system described in this paper was based on engineering prototype modules containing 2-junction cells. Semprius' product will be a cost-optimized HCPV module array based on a transfer printed 3-junction cell. Such a module is being developed and a 2.5 kW RD&D system based on this module will be installed in 2011. This module has a geometric concentration ratio of 1100X, a form factor of 24"x18"x2.5" and a module efficiency of >30%. Figure 16 presents the aperture efficiency of such a module, measured at Semprius over the course of a day. The efficiency is uncompensated for temperature or spectrum. Semprius has also demonstrated cell efficiencies of 41.7% at 800X concentration on transfer printed cells. Figure 17 presents the dependence of efficiency on concentration ratio for such a cell, measured by NREL.

CONCLUSIONS

On-sun performance data from a novel micro-cell based HCPV system, installed in Tucson is presented. The system has operated for ten months with an average energy yield of >2500 kW/kWp and an average capacity factor of 29%. This data is compared with performance data from several conventional flat plate systems in the same test yard. It was found that the energy yield of the HCPV system is two times higher than that of the next best performing technology on sunny days. Three month average energy yields from August to November show the

Semprius HCPV system to produce 1.5 times more energy than the best performing TF-Si system per Wp installed. Semprius is currently developing a commercial product which will be field tested as a 2.5 kW system in 2011.

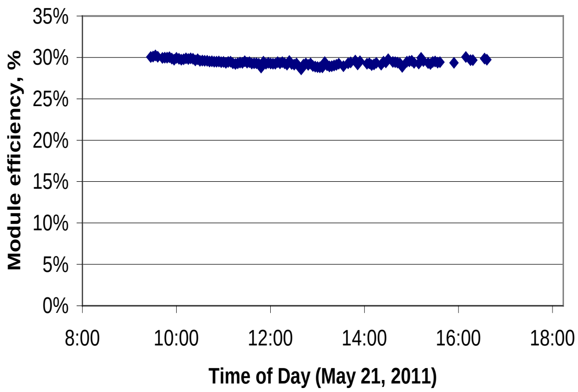

Figure 16: Semprius module aperture efficiency

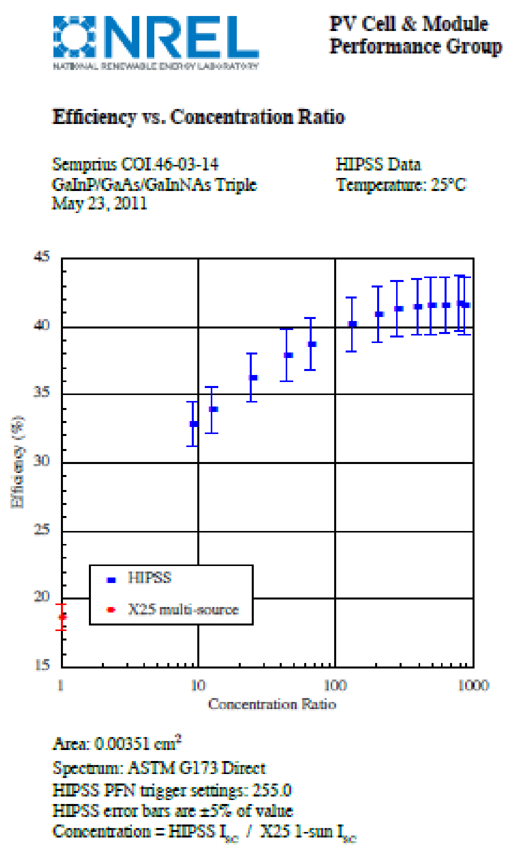

Figure 17: Efficiency versus concentration plot for transfer printed 3J cell, measured by NREL.

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