Supplemental Information

This document provides supplemental information and explains the content found in the files (OSA_SOLAR12_12113_final.pdf and Solyndra_Data.pdf) that you can download. The reference for the former is:

R. John Koshel, Greg P. Smestad, Daniel Shull, Peter Stephens, and Tim Healy, "Cylindrical and Flat Solar Collector Geometries: Theory and Experiment - The Performance and Optics of the 'Solyndra' PV Panel", Optical Society of America (OSA) Meeting, SOLAR 2012, Eindhoven, The Netherlands, Nov. 13, 2012.

Prior Work and its Application

The following NASA/DOE paper describes a similar geometry and optics as was found in Solyndra's products.

D. C. Beekley and G. R. Mather, Jr., Analysis and experimental tests of a high-performance evacuated tubular collector, DOE/NASA CR-150874, Publication Date: 12/1978. A PDF is available online:

http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19790008199_1979008199.pdf

This contains the theoretical analysis that we utilized. A basic understanding of the geometry and results can be obtained from figs. 5, 9 and 10 of this publication.

The optical geometry of the Solyndra product is shown on slide 4 of 28 (OSA_SOLAR12_12113_final.pdf). Sunlight is directly incident on the upper surface of a tube throughout the day. One tube alone is an interesting solar collector, but an array of tubes is necessary to cover a larger area. Depending on the angle of incidence, light can also fall between adjacent tubes where it's reflected by the backplane. Some, but not all, of this light can reach the under surface of the tubes. The arrangement of an array of cylindrical tubes in front of a reflector can thus be thought of as a solar concentrator with losses.

Further complexities are shown in the upper right of slide 4 of 28. The optical matching fluid between the two tubes allows the surface of the CIGS to appear magnified (enlarged). Light incident on the surface of the larger tube is refracted towards the Copper Indium Gallium Diselenide (CIGS) deposited on the inner, smaller tube where it is absorbed and converted to electricity. For initial studies, it is recommended that a simplification be utilized when applying the NASA/DOE publication to the Solyndra panel. We modeled the Solyndra system as if the CIGS solar absorber was on the outside of a tube of D_6 = 22 mm, thus neglecting some of its complexities and multiple interfaces.

At large angles of incidence, shadowing can occur between neighboring tubes. Light can also be blocked to the back reflector. For the case of $d = 2D_6$, light incident at angles greater than plus and minus 60 degrees (the critical angle measured from the panel normal) is blocked by adjacent tubes. This light does not reach the backplane reflector and for this case, the panel behaves much like a flat plate module. This is shown on page 12 of 28.

Backplane (Reflector) and its Nature

The additional experiments (Solyndra_Data.pdf) and the original work (OSA_SOLAR12_12113_final.pdf) all utilized a flat, white reflector as the backplane when a reflector was used. The photographs show the flat, pigmented polyethylene sheet that was employed. It was diffusely reflective, in contrast to a specular reflector or a mirror. From measurements performed using a goniometer, laser and detector, it was determined that its angular reflectance profile approximates a Lambertian surface (http://en.wikipedia.org/wiki/Diffuse_reflection); it has a reflectivity of over 80% and scatters light in all directions.

Distance from the Backplane to the Tubes

In most of the theoretical work that we performed, the distance from the tubes to the reflector (or backplane) is 1.5 times the tube diameter. This is denoted as D(subscript)B or D_B. For the installed Solyndra system and for our experimental measurements, this distance is somewhat greater (27 cm = 270 mm). It is this value that should be used for any modeling or ray tracing that is to be compared to the Solyndra products. The results from the NASA/DOE paper suggested that D_B values greater than 1.5 tube diameters yield similar results for a white, diffusely reflective backplane. This was not studied experimentally in any detail.

Other Experimental Parameters

For both the modeling and experiments, the long axis of the tubes was oriented in a north-south direction. The tubes and the flat plate PV modules were oriented horizontally (e.g., no tilt) unless otherwise specified. The glass tubes are 103.5 cm long and yield a PV tube with an active area of 100 cm. The outside diameter of the tubes is 22 mm. Forty tubes were employed, resulting in a 1000 x 1804 mm overall system area ($d = 2D_6$). A Solar Frontier SC85-EX-B module was compared to SL-150-157 Solyndra module. Under typical irradiance and temperature conditions, two such horizontally-mounted Solar Frontier modules connected in series produce approximately the same voltage and current as the Solyndra module.

Contribution of the Backplane Reflector

We have determined the light collected by the array of cylindrical tubes without a reflector in the backplane. The left side of page 7 of 28 (OSA_SOLAR12_12113_final.pdf) shows on the theoretical results obtained from the NASA/DOE paper. This is labeled on the plot as *Direct on Cylindrical Tubes*. The right side shows the contribution of the white reflector. Their sum is the total irradiance on the array of tubes (from top and bottom illumination). This combined irradiance curve is labeled as *Cylindrical tubes* on slide 8 of 28 and is also displayed on slide 16 of 28. *Flat* is a normal, or standard, PV panel at the same tilt, or orientation, as the array of tubes. It serves as a "control" or reference and exhibits the expected cosine behavior (shape of the curve).

To study these aspects experimentally, we put a black blanket behind the tubes, but the distance between the tubes and the horizontal backplane was the same as was mentioned above. Slide 17 of 28 shows theory vs. experiment for the array of tubes with no reflector in the backplane. The theoretical and experimental results match very closely in terms of the shape of the curve, which resembles a catenary. A few experimental points were quickly checked with the white backplane added; these are indicated in the plot on the left side. This was accomplished by quickly removing the blanket, exposing the white, reflective backplane.

FRED

The results from ray tracing analysis performed using FRED (http://photonengr.com/software/) are shown as a line in slide 22 of 28, and this matches the shape of both the experimental curve and the theory from the NASA/DOE paper. This is for the combined effects of direct light to the tubes and the contribution from the diffusely reflective, white backplane. For this analysis, we modeled the Solyndra system using the two tubes and the complex optical geometry summarized on slide 4 of 28 (OSA_SOLAR12_12113_final.pdf). This includes the following values:

Soda Lime Glass (both tubes), refractive Index, n = 1.514
Outer tube: Outside Diameter 22 mm; wall thickness 1.35 mm (the data sheet says 1.2 mm, but 1.3 – 1.4 mm was measured).
Inner tube: Outside Diameter 15 mm; wall thickness 1.35 mm (the outside of the inner tube has the black CIGS solar cell deposited onto it)
The fluid in between the two tubes is XIAMETER PMX-200 Silicone Fluid 50CS, refractive index = 1.4022.
D_B should be taken as 27 cm or 270 mm.

Please let me know if you understand what we've done and if you have any questions. It is my intension to eventually publish a paper with the content that is described above.

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More information and photographs are found at the following webpage:
http://www.solideas.com/GlassTubes.html