REhnu dish-based CPV: Module performance and planned 100 kW plant

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Abstract. A REhnu CPV module uses a 2.6 m², back-silvered glass reflector to focus sunlight into a 150 mm diameter receiver housing 36 multijunction cells. Current modules use commercially available 8.8 mm cells operated at 950x concentration with a cell efficiency of 41% for an AM1.5 solar spectrum. Optics in the receiver format the sunlight to illuminate the cells which are mounted slightly apart on four flat circuit boards. Active cooling is provided by liquid circulated to a radiator which can easily be configured to also provide thermal energy in the form of hot fluid at an adjustable temperature up to 80 °C.

Modules mounted in pairs on a dual axis tracker have been tested in the field. Module conversion efficiency, corrected to 25 °C cell temperature (CSTC), is found to peak at 31.2% for air mass 2.75. The I-V curve shows that the concentrated sunlight is distributed between the cells with a uniformity of ±7%. Steps are now being taken to improve uniformity, to reduce infrared losses caused by iron absorption in the reflector glass and by the receiver’s antireflection coatings, and to upgrade to 42% efficient cells. Overall efficiency is projected to then increase to 35%. In hybrid mode (electrical + thermal) the total efficiency approaches 80%.

REhnu’s basic generator unit to be replicated for large scale installations has eight modules in a 2 x 4 array on a dual axis tracker. The first of these 6 kW units with mirrors of very low iron absorption glass has now been installed in the field, and 16 more units are under construction for a 100 kW, grid-connected plant at the Solar Zone of the University of Arizona Tech Park.

INTRODUCTION

Multijunction PV cells have the fundamental advantage of high conversion efficiency, twice that of silicon cells. Their high cost per unit area is overcome in CPV systems by using them in sunlight concentrated up to 1000x or more, resulting in a cell cost per watt several times less than for silicon. However, for complete CPV systems to exploit these advantages and beat solar energy cost from silicon panel systems, the required high optical concentration, cell cooling and dual axis tracking must be implemented at low cost.

Most current CPV modules package individual identical optical concentrators along with each CPV cell. This approach to concentration has the advantage of ensuring equal flux on each cell and providing a large area behind the cells for heat removal by natural convection. However, it has the disadvantage that the resulting modules are large packages requiring alignment and electrical interconnects over a large area, and the Fresnel lenses commonly used are lossy and have chromatic aberration.

REhnu’s approach uses large paraboloidal mirrors to concentrate sunlight, thereby exploiting much of the manufacturing technology and facilities already developed for thermal CSP systems. In this architecture, sunlight at the focus is converted into electricity in a receiver with many closely packed cells. The receiver is very small compared to conventional CPV modules of the same power, which should reduce the manufacturing costs. Even distribution of light between the cells is ensured by the optical design described below. Active cooling is required and adds some complexity but also is more effective than passive CPV cooling, resulting in increased conversion efficiency.
Electro-optical Design

The current standard REhnu module is a much improved version of an earlier implementation¹. It uses a 2.6 m² square paraboloidal dish of 1.5 m focal length and forms an image of the sun in the center of a spherical fused quartz field lens as shown in Fig. 1a. This lens forms a concave image of the primary mirror at 500x concentration which is stabilized against tracker pointing errors. The stabilization is shown in Fig. 1a by the on-axis rays shown in black and off-axis in red which both illuminate the same area at the secondary optics. These optics, in the form of an array of reflecting funnels, reformat the light into 12 rectangular areas of equal power at 950X concentration. The cells are located directly at the funnel exits².

MANUFACTURE AND ASSEMBLY OF SYSTEM ELEMENTS

Components for a 100 kW REhnu installation are currently being manufactured and assembled at REhnu’s own premises and under contract to the University of Arizona Mirror Lab and elsewhere.

Reflector Dishes

REhnu’s mirrors are replicated from a concave paraboloidal mold. A 1.65 m square sheet of flat glass placed over the mold is heated to ~ 600 °C, when it slumps into shape (Fig. 1b)⁴. After silvering and painting, mounting pads are attached (Fig. 1c). The pad mounting surfaces are coplanar, so installation or replacement does not require subsequent alignment. A batch of 150 mirrors is currently being made of Schott B270 glass.

Receiver

The REhnu 800 W receiver is shown in Fig. 2a. Sunlight enters through the ball lens on the right. The receiver

FIGURE 1. (a) Module ray diagram. (b) Glass 1.65 m square shaped in a concave paraboloidal mold. (c) Back of mirrors showing pads for attachment to the tracker.

FIGURE 2. (a) 800 W receiver. (b) One of four 200 W ceramic circuit boards in the receiver. (c) “Origami” secondary optics.
incorporates 36 triple junction cells mounted on four flat AlN circuit boards (Fig. 2b). The nine cells on each card are configured in three rectangular areas. An “origami” reflector (Fig. 2c) reformats the square mirror image formed by the ball lens into matching areas registering with the cell groups. The circuit boards are cooled by coolant flowing through microchannel heatsinks.

**10 kW Heat Exchanger**

Figure 3a below shows the heat exchanger made for the 8-module tracker. It is mounted directly on the elevation structure and serves as a counterweight. Coolant is circulated through the receivers to a 1.2 m square radiator at a flow rate of 0.9 l/sec by an Iwaki pump consuming 50 W of electrical power. Air is drawn through the radiator by a 1.2 m diameter fan with a direct drive motor which also consumes 50 W of electrical power. Dissipation of 10 kW is achieved at a temperature difference of only 6.6 °C between the temperature of the coolant returned to the receivers and ambient air. The total parasitic loss for active cooling of 100 W is a low 1.6% of the electrical output of 6 kW from the 8-M tracker.

For distributed installations where heat at temperature < 100 °C is valuable, heat can instead be extracted by a liquid-to-liquid heat exchanger. A large amount of thermal energy may be extracted at the cost of a small reduction in electrical power output due to increased cell operating temperatures. Thus if 10 kW is harvested in water at 80°C, resulting in a rise in cell operating temperature of 60 °C, the electrical output reduction from reduced efficiency is just 700 W.

**2-Module Trackers**

![FIGURE 3. (a) Heat exchanger on an 8-module unit. (b) 2-module unit at the University of Arizona campus.](image)

Modules are currently being field tested in two-module trackers designed for rooftop installation, as shown in Fig. 3b. The mirrors and the “T” cross bar post carrying both receivers and the heat exchanger are held by a torsion tube behind the mirrors.

**MODULE AND TRACKER PERFORMANCE**

The performance of the two module tracker on the University of Arizona campus was measured with reference to DNI measurements made close by at the Department of Atmospheric Sciences. The two modules are connected in series to a computer controlled load bank with I-V curves measured every five minutes throughout the day. The peak power derived from the IV curve is normalized by the total collected power, determined as the DNI multiplied by the collecting area, to derive raw system efficiency as defined by

\[
\eta_{raw} = \frac{V_{mp} \cdot I_{mp}}{DNI \cdot A}
\]

where A is taken to be the area of two full mirrors, 5.2 m². The raw efficiency when corrected to a standard cell temperature of 25 °C yields a temperature corrected system efficiency (CSTC).
Figure 4 shows measurement taken through a day in January 2016 with the 2-module system shown in Fig. 3b. The DNI, peaking at noon at about 1000 W/m², is shown as the top dot-dash line. Ambient and cell temperatures are the green and blue curves. The raw module efficiency is shown in black and the temperature corrected efficiency in red. The efficiency increases through the afternoon, because of spectral imbalance in the module, as discussed below. The maximum CSTC efficiency of 31.2% is reached at around 3:20 pm at air mass 2.75.

The I-V curve obtained at this maximum efficiency is shown in Fig. 5a. $V_{mp} = 69.5\, V$, $I_{mp} = 20.4\, A$ and $P_{DC} = 1417\, W$. The DNI at the time was 917 W/m² yielding a raw efficiency of 29.7%. The cell temperature at this time was 51 °C, and the ambient temperature 25 °C. Correcting to the standard 25 °C cell temperature yields the CSTC efficiency of 31.2% for the two 2.6 m² modules. Corrected to the standard operating condition of ambient air temperature of 20 °C, the CSOC efficiency is 30.0%.

Steps to Improve Module Conversion Efficiency

Several steps are planned and/or are already being implemented to improve the efficiency of the modules. The first is to improve optical throughput and spectral balance. The modules used to obtain the data above have significant losses in the ball lens and the mirror glass, particularly at longer wavelengths. The effect of the spectral imbalance causes the narrowest bandgap junction to be starved of light relative to the wider bandgap junctions.
Spectral measurements of the ball lens transmission and mirror reflectivity are shown in Fig. 6. Spectral imbalance accounts for the increase in conversion efficiency with increased air mass shown in Fig. 5b.

The ball losses are due to the single quarter-wave sol gel AR coating being too thin, averaging 99% transmission for the wide bandgap junction but 96% for the narrow bandgap junctions. The mirror losses are due to iron absorption in the PPG Solarphire PV float glass. The total optical path in these 4 mm thick second surface mirrors is 8 mm, resulting in the spectral reflectivity curve in Fig. 6. The combined throughput of the ball lens and mirror is shown in the dotted curve. The solar weighted transmission drops from around 92% in the wide band to 87% in the narrow band. The 5% transmission difference is consistent with the 0.8%/30.5% fractional decrease in conversion efficiency (2.6%) measured with solar reddening decreasing from 2.75 to 1.6 air masses.

To address the spectral imbalance we are now making the mirrors from Schott B270 glass which is free from iron absorption. We have also developed an improved double layer broadband AR coating for the ball lenses that largely removes the infrared loss. Correcting the imbalance and increasing the throughput overall is projected to increase the conversion efficiency by 2% from 31% to 33%.

A second type of reduction in conversion efficiency is caused by deviations from uniformity in the division of concentrated sunlight between the 12 cell groups in a receiver. This imbalance shows in the I-V curve of Fig. 5a as the difference between the short circuit current of 23.5 A to the 20.5 A max power current due to a spread of ±7% in illumination uniformity. We are able to measure the separate voltages and construct the I-V curves for the individual cell groups, thereby confirming the non-uniformity and indicating that redistributing the light to be uniform will increase the conversion efficiency by a further 1%. Improvements to the optical funnel geometry are being made to improve uniformity and obtain this increase. A third improvement in module efficiency is planned by upgrading from the present 41% cells to the most efficient 8.8 mm commercial cells, now 42% efficient at 950x concentration. Given all three improvements, we project a module CSTC efficiency of ~35%.

For a grid-connected 8-module system we expect overall system conversion efficiency of 30% CSOC (AC power out/sunlight input). The projected loss from module to overall efficiency is relatively small because the large square modules are densely packed on the trackers, and the parasitic loss from active cooling is equivalent to only 0.6% reduction in conversion efficiency. This small loss is compensated by the improved efficiency over passively cooled cells which operate at a higher temperature.

**8-M TRACKER AND 100 KW PLANT**

Construction of 8-module units on dual axis trackers, as shown in Fig. 7, has now started. The tracker structures are being fabricated by SOGO SA in Hermosillo. A 100 kW pilot plant (Fig. 8a) with 16 of these trackers is being built by REhnu and M3 Engineering at the University of Arizona Solar Zone under a PPA with Tucson Electric Power. Projected for completion in 2016, it represents the first phase of what will be a 1 MW plant (Fig. 8b).

**CONCLUSION**

Progress to date shows the overall viability of the REhnu’s large dish, high concentration approach to CPV, with 31% module conversion efficiency already demonstrated. As described above, steps now in progress at REhnu aim at improved optical throughput and balance and should increase the efficiency of our 2.6 m² modules to 35%, with
42% efficiency cells. In a few years, when commercial cell efficiencies are expected to reach 50%, REhnu modules will scale to 42% CSTC conversion efficiency. The efficiencies quoted above refer only to electrical power output as in the Tech Park project. However, by taking advantage of the thermal output available from REhnu modules, total energy collection efficiency close to 80% can be realized. Applications of this hybrid mode are envisaged for large buildings, factories, data centers, resorts, mines and desalination, among others.

The cost of the 8-module trackers now being made for the 100 kW pilot plant is $8/watt, a reasonable amount considering our current very low volume. Our cost is projected to drop to $5/watt at the next level of 1 MW, requiring 160 8-module trackers, well within REhnu’s manufacturing capacity. REhnu is thus now at a stage where only modest further development investment is needed to take a very significant step toward larger scale generator plants.

FIGURE 7. REhnu’s 8-M tracker with mirrors installed at the Green Valley Pecan Company in Arizona.

FIGURE 8. Artists rendition of (a) 100 kW plant with (16) 8-M trackers and (b) built out to 1 MW on the UA Tech Park site.

REFERENCES