Evaluation Of Electrical And Thermal Performance Of A Linear Hybrid CPV-T Micro-Concentrator System

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Abstract. Chromasun Inc. and The Australian National University have developed a low-concentration, linear, hybrid micro-concentrator (MCT) system suitable for urban rooftop installation. The system produces both electrical and thermal power, integrating the functionality of separate flat plate photovoltaic and solar hot water systems. The MCT system utilises industry-standard components, including modified mono-crystalline silicon one-sun solar cells, commonly used in flat panel applications. The MCT manufacturing processes are designed around low-cost methods, and tap directly into existing economies of scale. Initial test results without any system optimisation has demonstrated an electrical output of more than 300 W, and a thermal output of more than 1500 W at 950 W/m^2 DNI.

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INTRODUCTION

Concentrating photovoltaic (CPV) systems offer several advantages over flat plate photovoltaic (PV) systems, including lower levelised cost of energy through the replacement of costly solar cells with inexpensive optics and tracking systems. Hybrid CPV-thermal (CPV-T) systems also allow capture of what would otherwise be waste. Conventional CPV-T systems are significant structural installations, and generally unsuitable for domestic and commercial rooftop applications.

Large ground-mounted utility-scale power generation systems use expensive, specialist solar cells placed under high concentration ratios of up to 1000X [1]. Comparatively limited research and development of low concentration systems for small-scale urban rooftop environments has been undertaken on a global scale. Substantial urban domestic markets would be well served by hybrid systems of up to 50 suns concentration. By reducing the concentration ratio the demands on optics, tracking, thermal management, and maintenance are significantly reduced in comparison to high concentration systems.

Low-concentration CPV and CPV-T system development is hampered by a lack of reasonably-priced, commercially-available solar cells at industrial volumes [2]. One possible solution to this problem is to modify one-sun mono-crystalline silicon solar cells.

In order to enter the rooftop urban market, CPV systems must be low maintenance, reliable, easy to operate, be economically mounted on conventional roofs, and perform effectively and reliably for 25 years or more. The materials, construction, and installation costs need to be kept to a minimum.

Conventional linear CPV systems are generally quite heavy, and require significant structural support to provide the required rigidity and focal performance. The large open mirror areas are exposed to hail, snow, rain, dust, and other soiling sources. The entire exposed system is also subject to significant wind loading. To accommodate this exposure requires the entire structure to be manufactured to high tolerances in order to ensure flux uniformity on the receiver in the presence of distortion by gravitational loading, wind loading, and thermal expansion [3],[4]. These requirements generally mean that the systems are significant structural installations.

In general, economies of scale with conventional linear concentration systems have yet to be realised; hence any technology that can make use of existing industrial production technologies is likely to have a significant cost and performance advantage.

A joint research venture between the Centre for Sustainable Energy Systems at the Australian National University and Chromasun Inc., a San Jose-based company, has developed a hybrid linear CPV-T system designed specifically for urban, domestic, and industrial rooftop applications [5]. The development of the MCT system was motivated by the performance and cost benefits of on-site generation of both thermal and electrical energy. This paper presents an overview of the MCT system structure, receiver design, and initial results from a full hybrid system.

THE MCT SYSTEM CONCEPT

The concept governing the MCT system development was reduction of the size, weight, and profile of all components, incorporating the entire functional system into a low-profile, aesthetically-pleasing sealed enclosure. The 'black box' approach simplifies installation and maintenance.

FIGURE 1. Three light-weight, low area-loading MCT units mounted on a demonstration rooftop on the same support frame as the surrounding flat-plate PV panels.

MCT system receivers can be thermal only; providing thermal output at up to 220 ºC, or hybrid CPV-T providing both electrical and thermal energy outputs, with the thermal output temperature suitably limited by the PV element operational requirements. The compact form of the MCT, and the identical enclosure and optical and tracking system designs for both CPV and CPV-T applications, allows the MCT units to be installed in a modular, demand-specific configuration providing the required mix of electrical and thermal energy. MCT units can be densely packed in a similar fashion to flat plate PV systems, and can be mounted on the same supporting frame as PV panels, as shown in Figure 1.

The MCT system features a sealed enclosure 3.0 m long, 1.2 m wide, and 0.3 m deep. This isolates all the functional components of the system from the external environmental. Removal of wind loading on the optical system allows the use of a Fresnel array of ultra-lightweight reflectors, shown in Figure 2. This reflector system requires no structural support other than tensioning of the elements at the mirror-mounting points at each end of the enclosure.

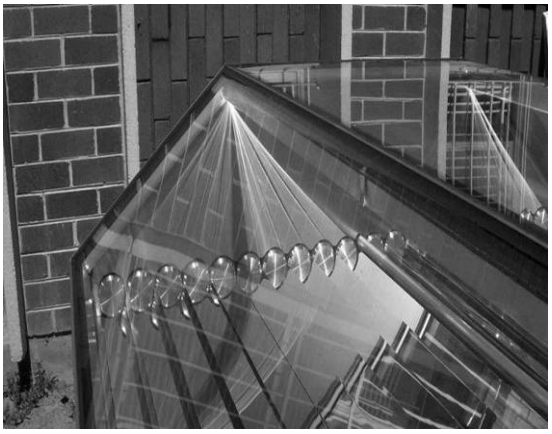

FIGURE 2. The light-weight Fresnel reflector array on-sun, with each element individually tensioned. The focal characteristic of the array is visible on the MCT end-plate.

Eliminating internal support structures significantly reduces material, manufacturing, and assembly costs. Simplification of the optical and tracking systems enables the entire MCT system to have a low gross weight with an area loading less than 30 kg/m^2. This makes the MCT suitable for general rooftop installation, including most domestic roofs, with no structural alteration required. The sealed enclosure is also aesthetically designed for broad consumer appeal.

Isolation from the external environment increases the lifetime of the system components, and reduces or eliminates maintenance costs. System construction can occur off-site, and installation is similar to flat plate PV and solar hot water systems.

THE MCT HYBRID RECEIVER

The MCT hybrid receiver consists of a series of sub-module assemblies thermally bonded to the base of a channel in an aluminium extrusion which incorporates a cooling fluid channel along the rear of the extrusion.

Hybrid Receiver CPV Cells

A fundamental problem hampering the commercial development of low to medium concentration CPV systems is the lack of commercially available cells. When planning the MCT system design, a strategic decision was made to modify commercially available, high-efficiency, one-sun solar cells for use under concentration. Significant development work has produced suitably modified one-sun cells with efficiencies in the range of 19 to 20% at concentration ratios between 15 to 30 suns.

Hybrid Receiver Sub-module Elements

Modified one-sun solar cells are integrated into a sub-module using a monolithic substrate incorporating structural support, heat sinking, electrical isolation and interconnection, and integrated bypass diode protection of individual series-connected cell strings.

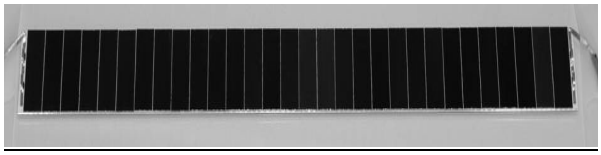

FIGURE 3. A sub-module incorporating 30 modified one-sun solar cells

By surface mounting the cells using a custom reflow process, sub-modules such as that shown in Figure 3, incorporating by-pass diodes with all elements heat sunk, can be produced with inter-cell spacing as little as 100 μm.

Hybrid Receiver Thermal Interfaces

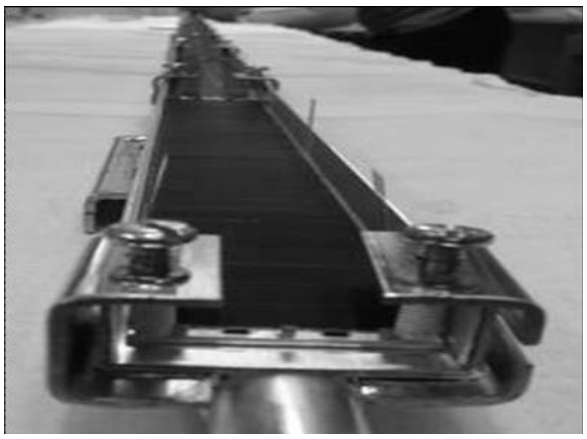

FIGURE 4. Sub-modules mounted and clamped in the extrusion channel.

Ten substrates, each with 30 cells, are mounted in each receiver using a highly thermally conductive adhesive, as shown in Figure 4, cured for 90 minutes at 100 ºC by circulating a heating fluid through the back of the receiver. The sub-modules were then electrically interconnected in series and hi-pot isolation tests were performed.

Hybrid Receiver Encapsulation

The receivers were encapsulated with silicone and cover glass, as shown in Figure 5, for protection and refractive index-matching. When correctly encapsulated, the efficiency rises by around one percentage point absolute compared with a similar arrangement tested in air.

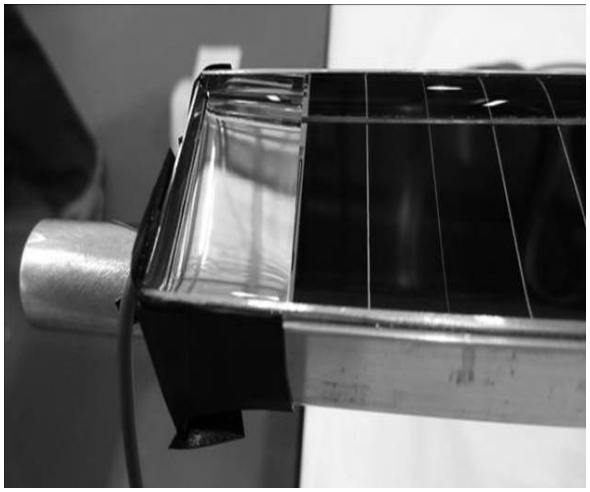

FIGURE 5. Encapsulated receiver end-view, showing the reflective strip that covers sensitive components.

Hybrid Receiver Mounting In The MCT

FIGURE 6. Receiver mounted in an open MCT.

The receivers were mounted in the MCT as shown in Figure 6, and the system was plumbed. The receivers were connected in series to create a high voltage, low current system. Connecting receivers in parallel can reduce the effects of optical mismatch.

MCT SYSTEM PRELIMINARY TESTS

Prior to mounting in the MCT the receivers were tested and the bypass diodes checked by shading areas of the module.

FIGURE 7. The prototype hybrid CPV-T MCT system on-sun and tracking.

Figure 7 shows the enclosed system on-sun and tracking during the testing procedure. A combination of manual methods was used to take the data because the purpose-designed test system required for high-voltage IV curve measurement was not yet completed.

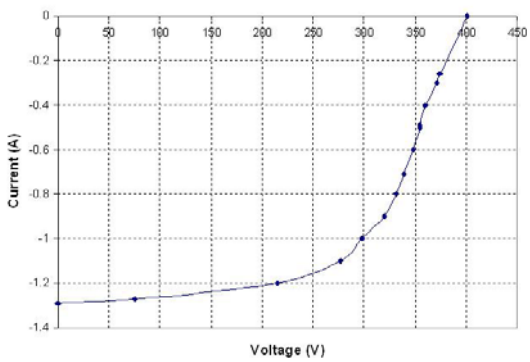

FIGURE 8. A manually measured and generated IV characteristic of the MCT CPV-T prototype.

The measurements reported here, shown in Figure 8, using a digital multi-meter and a manually variable load provide an indication only of system performance and show at least one sub-module in each receiver non-operational due to the sub-optimal incident angle; decreasing electrical output by at least 10%. The calculated electrical power output was approximately 305 W, and the calculated thermal output was approximately 1580 W. A full control and data acquisition system is under development.

CONCLUSION

Fully-functional hybrid CPV-T receivers developed at ANU have been demonstrated in the Chromasun MCT system. The receivers are based on commercially-available one-sun solar cells that have been modified to operate under concentration. The monolithic sub-module assemblies with integrated heat-sinking and bypass diodes are designed for high electrical and thermal performance using modified industry-standard materials and adapted assembly processes. The assembly procedures incorporate low-cost manufacturing processes and materials to directly tap existing economies of scale for immediate benefit.

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