ELECTRICAL AND THERMAL PERFORMANCE OF THE ANU-CHROMASUN MICRO-CONCENTRATOR SYSTEM

V. Everett[1], J. Harvey[1], M. Vivar[1], E. Thomsen[1], M Fuentes[2], M Ebert[3], P. Le Leivre[4], M. Greaves[4], A. Tanner[4], A. Blakers[1],
[1]Australian National University, Canberra, ACT, Australia:
[2]University of Jaen, Jaen, Spain;
[3]University of Applied Science Berlin, Berlin, Germany;
[4] Chromasun Inc., San Jose California, USA.
Corresponding author: Vernie Everett, phone: +61 2 6125 8872, email: vernie.everett@anu.edu.au

ABSTRACT: The Australian National University, in partnership with Chromasun Inc., have jointly developed a hybrid linear CPV-Thermal (CPV-T) system designed specifically for roof-top applications. The micro-concentrator (MCT) is a fully sealed, light-weight structure with a low wind-load factor. It incorporates modified one-sun solar cells operating at around 20X geometric concentration and 12 to 15 suns effective optical concentration, and uses a novel, ultra-lightweight Fresnel array with closed loop tracking to produce electricity, as well as thermal energy suitable for generating hot water or running absorption chillers. The development of this system was motivated by the demonstrable benefits of on-site generation of both thermal and electrical energy, with a higher combined efficiency and reduced roof-top footprint, than independent, conventional PV arrays and solar hot water systems. The compact form-factor allows for the installation of multiple MCT units, comprising a range of hybrid and thermal-only units to satisfy site requirements, with the low-profile form-factor providing a less obtrusive, aesthetically-pleasing installation. Several hybrid CPV-T MCT prototype systems have been constructed and are in various stages of testing. Preliminary electrical and thermal performance data will be presented.

Keywords: Micro-concentrator, CPV, PV-Thermal hybrid, CST.

1 INTRODUCTION

Concentrating photovoltaic (CPV) systems offer the opportunity to realise several advantages over flat plate photovoltaic (PV) systems. The most significant advantages include lower levelised cost of energy through the replacement of costly solar cells with inexpensive optics and tracking systems, along with the possibility of recovering thermal energy, which is generally lost as waste heat in conventional PV systems. Hybrid CPV-thermal (CPV-T) systems allow capture of what would otherwise be waste heat. Conventional CPV-T systems are generally significant structural installations, making them unsuitable for domestic and small-scale commercial roof-top 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 on a global scale has been undertaken in the field of low concentration systems for small-scale urban rooftop environments. Market research has indicated substantial urban domestic markets that could utilise thermal energy at the point of production would be well served by hybrid systems of up to 50 suns concentration.

Reduction in the concentration ratio does reduce efficiency. However, with careful planning and design, this reduction can be offset by relaxing the demands on precision optics, high-accuracy tracking, demanding thermal management, and expensive system operation and maintenance costs when compared with high concentration systems.

The development of conventional low-concentration CPV and CPV-T systems has been hindered by the lack of reasonably-priced, well-performing, commercially-available concentrator solar cells at industrial volumes [2]. Since this is a relatively small commercial market it is difficult to realise the economies of scale required for significant cost reduction in cell fabrication. In order to circumvent this problem, an early design decision was made to modify one-sun, mono-crystalline silicon solar cells for use as concentrator cells.

The urban domestic and commercial roof-top market presents a demanding performance and design space. For ready market acceptance, CPV-T systems must be low maintenance, reliable, and easy to operate. In order to be widely acceptable for retro-fitting, they must be able to be economically mounted on existing conventional roofs, preferably with no structural alterations, perform effectively and reliably for 25 years or more, and be aesthetically acceptable. The materials, construction, and installation costs obviously need to be kept to a minimum.

Conventional linear CPV and CPV-T 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 conventional CPV-T 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 dictate that the systems are significant structural installations.

In general, economies of scale with conventional linear concentration systems have yet to be realised; hence any new technology that can directly tap in to 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 ANU-Chromasun MCT system was motivated by the performance and cost benefits of on-site generation of both thermal and electrical energy. This paper presents a brief review of the MCT system structure and design, and initial results from full-time operation of a full PV-Thermal prototype hybrid system.

2 BRIEF DESIGN OVERVIEW

The considerations driving the MCT system development included reduction of the size, weight, and profile of all components; incorporating the entire functional system into a low-profile, aesthetically-pleasing sealed enclosure, and utilising as many ready-made components or easily-modified elements as possible in order to directly tap in to existing economies of scale for commercial production. The 'black box' approach simplifies installation and maintenance.

The MCT systems 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 PV operational requirements. The compact form of the MCT, the identical enclosures, and identical 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. MCT units can be densely packed in a similar fashion to flat plate PV systems, and can be mounted on similar supporting frames to those used for PV panels.

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. The ultra-lightweight reflector array weighs only a few kilograms and requires no structural support other than tensioning of the elements at the mirror-mounting points at each end of the enclosure.

Eliminating internal support structures, particularly those related to the optical system, 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 of the system components from the external environment increases the component lifetime, and reduces or eliminates associated maintenance costs. System construction can occur entirely off-site, and the MCT system installation is similar to flat plate PV and solar hot water systems.

2.1 Hybrid PV-T Receivers

One-sun mono-crystalline silicon solar cells are modified to function efficiently as concentrator cells and are integrated in sub-module elements using a monolithic commercially-available substrate that incorporates structural support, heat sinking, electrical isolation and cell interconnection, and integrated bypass diode protection of individual series-connected cell strings.

Ten modular substrates, each consisting of 30 series-connected cells, are mounted in each 3-metre long receiver, of which there are two in each MCT unit, using a highly thermally conductive adhesive. The sub-modules were then electrically interconnected in series. The nominal output of a complete 3-metre long receiver is around 1.2 A I_{sc} and 200 V V_{oc} when operating at around 15 suns optical concentration.

2.2 Sub-module performance

Initial characterisation of pre-production prototype sub-modules, comprising 30 modified cells as detailed above, has demonstrated an STC electrical efficiency of approximately 18% when operating at 15 suns optical concentration. In this paper, performance data will be presented for the first production prototype of a hybrid MCT system rooftop mounted in South-Eastern Australia. Performance characterisation is extended to include average thermal and electrical yield over extended periods of operation. Thermal-only MCT systems are currently in deployment with select partners in several countries, and the hybrid CPV-T MCT is entering the field test phase with prototype installations in the US and Australia initially..

3 PROTOTYPE MCT THERMAL AND ELECTRICAL PERFOMANCE

The first production prototype of a hybrid MCT system rooftop, mounted at The Australian National University in South-Eastern Australia, has been characterised. The electrical and thermal performance characteristics have been obtained under outdoors, on-sun test conditions with the MCT system operating at ANU. The system was mounted on the rooftop of the Engineering Building, as shown in Figure 1.

Figure 1: First prototype MCT system mounted and operating on the roof-top test platform at ANU.

3.1 Thermal Performance

The MCT is designed to be versatile in configuration and to easily match customer demands, with the MCT readily arranged for either hybrid linear CPV-T or thermal only operation, simply by the choice of appropriate receivers. All system components, other than the receivers, are identical. In the hybrid system configuration, MCT's can provide combined-system electrical energy and hot water at a temperature range between 50 and 70 ℃.

The cooling circuit on the prototype system consisted of an immersed water pump in a small un-insulated storage tank. The cooling water was pumped through the PV-T receiver with a small electrical circulating pump. The cooling circuit was equipped with waterproof K-type thermocouples at the inlet and the outlet as well as a flow meter to measure the fluid flow, and a control valve to regulate the flow rate.

The storage tank was filled with ordinary tap water. As an alternative, for constant temperature inlet, the circuit can be directly connected to the tap.

Thermal data was collected by using a Datataker DT80. Table 1 shows the thermal output of MCT system for both series and parallel interconnection of the two receivers. The data presented here are instantaneous performance measurements that are representative of general system performance under these test conditions.

Table I: Thermal output and thermal efficiency for series and parallel configurations.

	Flowrate (Kg/s)	T(in) ^{o}C	T(out) ^{o}C	Thermal output (Wth)	Thermal Efficiency %
Par.	0.091	35.6	42.0	2416	69.2
Ser.	0.091	35.6	42.1	2375	68.2

Instantaneous thermal performance, shown in Table II, was obtained for optimal MCT inclination, with a tilt angle of 47 degrees and a N-S MCT orientation. DNI at the time was 997 W/m^2, and the ambient temperature was 18.4 ^{o}C. It is recognised that a stated DNI of 997 W/m^2 may raise some questions, but Canberra is at a modest altitude of 640 metres, and is blessed in winter with remarkably clear skies.

Table II: Instantaneous thermal output and thermal efficiency for a parallel configuration.

	Flowrate (Kg/s)	T(in) ^{o}C	T(out) ^{o}C	Thermal output (Wth)	Thermal Efficiency %
Par.	0.093	35.6	42.2	2540	71.0

These thermal performance results illustrate the outstanding capability of the MCT. While it is true that the system was operating far from stagnation for these tests, it also needs to be kept in mind that this prototype has not been optimised thermally. The receiver was not insulated, being mounted in an inverted cavity that provided minimal insulation from surrounding air. Furthermore, the mounting channel was not thermally isolated from the exterior aluminium extrusion of the frame. This latter feature has been remedied in subsequent designs, with the receiver mount in the newer design is thermally isolated from the exterior frame.

At these low operating temperatures the system operates at close to maximum thermal efficiency, around 70%, since the actual thermal losses are minimised

3.2 Electrical Performance

The electrical performance testing was conducted using a capacitive electronic load to test the receiver outputs within the enclosure under a range of flow rates. Effectively, this should translate to different cell temperatures. Under the present test configuration there is no capability for directly measuring cell temperatures, although close estimates can be obtained from the illumination intensity, calculated from the short circuit current, the open circuit voltage as a function of illumination, and a knowledge of the thermal coefficient of the cell.

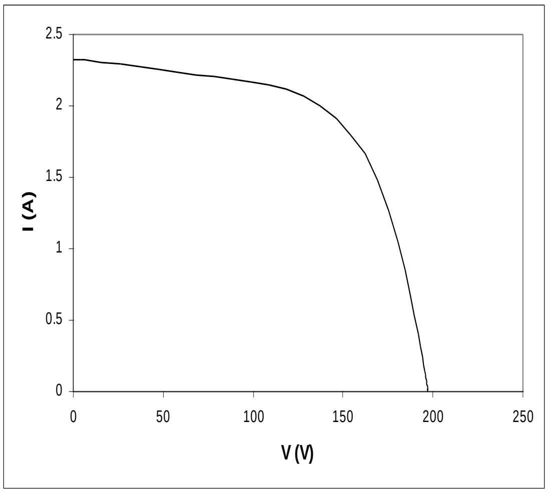

Figure 2: IV curve showing electrical output characteristic for a parallel receiver connection configuration

The maximum power point output for this receiver configuration, with an inlet temperature of 35 ^{o}C and an outlet temperature of 45 ^{o}C is 280 W. Detailed results are shown in Table III. Note that these electrical performance results correspond to the thermal data presented in Table II and were obtained under the same weather conditions with measurements conducted only a few minutes apart.

Table III: Instantaneous electrical output for a parallel configuration of the two MCT receivers.

Parameter	Value
Open circuit voltage (V)	197.3
Short circuit current (A)	2.33
Maximum power (W)	280.2
MPP current (A)	1.92
MPP voltage (V)	146.2
Fill factor (%)	61

Multiple MCT units can be electrically connected in series or in parallel, depending on inverter input requirements. However, it is likely that optimal system performance will be realised with multiple MCT units electrically connected in parallel because of current mismatch that will arise from independent tracking and other system performance features that may cause individual receiver currents to be less than ideally matched.

Similarly, multiple MCT units can be thermally connected in series or parallel, although again, optimal system performance will probably be achieved with units thermally connected in parallel to obtain better uniformity of voltage outputs across ganged MCT units. Alternatively, individual MPP trackers and micro-inverters could resolve the problem, albeit at some increased cost. For larger systems, a calculated arrangement including both series and parallel interconnection will result in optimal system performance. This will also need to include flow requirements in order to obtain turbulent flow regimes for maximum heat transfer from the receiver body to the thermal transfer fluid. Tests to date have indicated that the system is quite insensitive to flow rates, since the thermal transfer channel cross section is quite small, resulting in turbulent flow regimes being easily obtained with very low bulk flow rates.

More hybrid PV-T MCT units are presently being constructed and tests will be conducted to verify system modelling covering various operating arrangements.

3.3 Full day performance

The hybrid MCT was operated over the span of a full day and performance was logged as a function of time. The day was clear and sunny, with light winds. The results are shown in Figure 3.

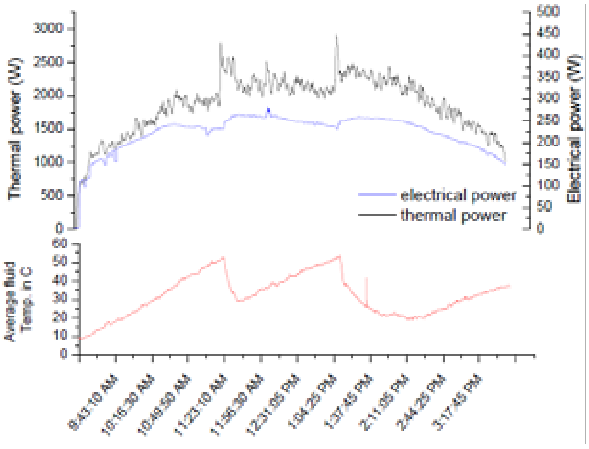

Figure 3: Electrical and thermal output for a parallel receiver connection configuration over the span of a day.

It can be seen in Figure 3 that the electrical output power dropped as the thermal output temperature rose, as expected. due to the negative thermal coefficient of the silicon cells. The magnitude of this effect will depend on the operating algorithm, ranging from negligible in change for constant temperature output, to maximum variability for constant flow rate operation. In practice, the actual operating mode will generally fall between these two extremes.

Furthermore, for this series of tests, the thermal transfer fluid flow rate was controlled so that it did not exceed 60 ^{o}C. The temperature peaks can be seen to correspond to the electrical power output troughs, with electrical output increasing as temperature decreases with higher fluid flow rate under similar irradiation levels. The interplay between irradiance, temperature, and electrical output is clearly illustrated in Figure 3.

4 CONCLUSION

The results presented here confirm preliminary modelled system performance conducted by Chromasun [5]; at least for the low temperature operating range, and exceed anticipated performance expectations at the operating temperatures encountered in these experiments. At normal operating conditions it can confidently be expected that combined electrical and thermal system performance will significantly exceed 70%. Thermal optimisation is presently being pursued, and extensive reliability and accelerated lifetime testing is under way.

These results confirm the assumptions made and the practicality of the design approaches. Further optimisation and development of system reliability will establish the MCT concept as a practical commercial option for on-site generation of thermal and electrical power in a versatile and adaptable, affordable and reliable system.

5 REFERENCES

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