A solar concentrating photovoltaic / thermal collector

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Abstract

Australia is a good location for solar concentrator applications. Current activities in Australia in this area are summarised. The Combined Heat and Power Solar (CHAPS) collector, under development by the Australian National University, is described in detail, and some measured performance indicators are presented. The thermal performance of the CHAPS collector is compared to a good quality flat plate hot water collector. Some of the technical challenges in the design of the CHAPS collector are discussed, in particular, the impact of non-uniformities in the illumination of the solar cells.

1. INTRODUCTION

The Centre for Sustainable Energy Systems at the Australian National University (ANU) has developed a photovoltaic/thermal collector with geometric concentration ratio of 37x. The so-called Combined Heat and Power Solar (CHAPS) collectors consist of mirrors that focus light onto high efficiency silicon solar cells to generate electricity. A fluid passes behind the cells to remove excess thermal energy and to heat water. The system is suited to installation on residential, commercial and light industrial buildings, to contribute to building heating, hot water and power requirements. The first commercial scale demonstration of the single-axis tracking CHAPS technology is a 300 m² system providing electricity and hot water for Bruce Hall, a residential college at the ANU. The primary advantage of the CHAPS system is that concentrating light allows a significant reduction in the area of solar cell coverage, the main cost driver in a flat plate system. A secondary advantage is the efficient use of space inherent in combining electrical and thermal energy generation. The aim in the development of the CHAPS collector is to capitalise on these advantages to produce photovoltaic power and solar hot water at a cost lower than possible with current technologies.

2. AVAILABILITY OF THE SOLAR RESOURCE IN AUSTRALIA

Australia has relatively high solar insolation, as shown in figure 1. The best solar conditions are in central and western Australia. As figure 1 shows, most of the population lives in the southern and eastern coastal areas; however, the electricity grid already extends into areas with good solar radiation, and therefore solar power is a feasible option for the future energy needs of most Australian households.

Solar concentrators make use of direct radiation only, and are suited to regions where the cloudiness is low, which is typically in arid regions. Australia is one of the hottest and driest countries in the world and has excellent solar conditions for concentrators.
3. CONCENTRATOR SYSTEMS IN AUSTRALIA

Australian companies and research institutions have long held an interest in concentrator systems, in the fields of both photovoltaic and solar thermal power generation. Some of the recent projects in Australia are identified below.

Melbourne based company Solar Systems have been working on dish photovoltaic systems for some years, and recently commissioned a 220 kWp system supplying power to a mini-grid that serves the indigenous community on the Anangu Pitjantjatjara lands in central Australia (Lasich, 2003). The system comprises ten 130 m$^2$ dishes, each with 112 spherical mirror panels focusing light onto a 0.23 m$^2$ receiver which uses silicon concentrator solar cells. A further three projects of a similar size are planned in central Australia. Solar Systems are also involved in a collaborative project with Australia’s Commonwealth Scientific and Industrial Research Organisation (CSIRO) to produce solar-enriched fuels and synthesis gas from methane using their dish technology.

Combined research between the University of Sydney and the University of New South Wales has led to the development of the Compact Linear Fresnel Reflector (CLFR) technology (Mills and Morrison, 2000). Multiple ground-mounted mirrored troughs, which are cleverly arranged to minimise ground coverage, focus light onto a cavity receiver with an array of boiling tubes to achieve direct steam generation. The plant is designed to supply heated feedwater into the steam cycle of a conventional coal-fired power station. The first prototype system consists of 1400 m$^2$ of reflectors supplying 265°C and 5 MPa wet steam to the Liddell power station, which is a coal-fired power station in the Hunter Valley in New South Wales. If the technology proves successful, it is planned to scale up the collector area at the power station to 26,500 m$^2$, and eventually to 132,000 m$^2$. 

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At the ANU, the use of dish concentrators has been advocated since the 1970’s. A dish pilot facility (fourteen 20 m$^2$ dishes) using a 25 kWe water/steam engine-generator was built and tested in the 1980’s to power the remote Australian township of White Cliffs (Kanef, 1987). In 1994 the ANU built the prototype 400 m$^2$ “Big Dish”, connected to a 50 kWe steam engine (Lovegrove et al., 2003). The ANU has also worked on solar dish concentrator systems incorporating thermochemical storage of energy using ammonia (Lovegrove et al., 2004).

The development of the CHAPS systems was preceded by PV trough technology development at the ANU since the mid-1990s, culminating in the commissioning of a 20 kW two-axis tracking passively cooled PV trough array at Rockingham, Western Australia (Smeltink et al., 2000).

### 4. DESCRIPTION OF THE CHAPS SYSTEM

The CHAPS mirrors reflect light onto receivers at the focus of the trough to generate electricity. The receivers have a conduit through which fluid passes to remove excess thermal energy and to heat water. This is shown diagrammatically in figure 2.

![Figure 2. Schematic diagram of the CHAPS system.](image)

The CHAPS collectors are made up of 1.42 m long mirrors and receiver modules, which are connected end-to-end to form a row. The mirror, receiver and solar cell widths are 155 cm, 8 cm and 4 cm respectively, which gives a geometric concentration ratio of 37x excluding the shading due to the receiver. The first CHAPS prototype is a single trough with 10 mirrors, pictured on the left in figure 3. The first commercial installation of the CHAPS technology is the Bruce Hall CHAPS system, pictured on the right in figure 3.

![Figure 3. The long trough CHAPS prototype (left), and the Bruce Hall CHAPS system under construction (right).](image)
The 300 m² demonstration system will provide electricity and domestic and heating hot water for Bruce Hall, a residential college at the ANU. There are eight collectors, each 24.5 m long consisting of 17 individual mirrors. The collectors are connected via pipes to two 6.5 m³ hot water storage tanks located in the basement of the building. The tanks have been sized so that enough energy is stored on a sunny day to meet the hot water load (mostly showers) the next morning. The tanks will also provide hot water for an in-floor hydronic heating system. The PV array is grid-connected via a 40 kW inverter. The Bruce Hall CHAPS system is currently under construction and is due for completion in mid 2005.

The parabolic mirrors were developed at the ANU and follow on from similar development of three-dimensional curved mirrors for dishes (Johnston et al., 2001). The reflective surface is a glass-on-metal laminate (GOML). The mirrors are around 93.5% reflective, and the glass surface is highly scratch resistant. While the geometrical concentration ratio is around 37x, the illumination flux intensity is far from even across the width of the solar cell. Under good sunlight conditions, the centre of the focal beam may have flux intensities upwards of 100 suns.

Monocrystalline silicon solar cells designed for concentrators are produced at the ANU for the CHAPS systems. The main difference between concentrator cells and normal one-sun solar cells is that they have much lower series resistance in order to handle the far higher currents. Figure 4 shows that the cells have narrow spacing of the conductive fingers, which is one technique used to reduce series resistance. Most cells are around 20% efficient at 25°C under 30 suns concentration.

![Figure 4. ANU concentrator cell.](image)

The receiver is built upon an extruded aluminium spine (figure 5). The solar cells are bonded to the extrusion and encapsulated with silicone and glass. The back and sides of the receiver are insulated with rockwool encased by an aluminium cover.

![Figure 5. Cross-section of a CHAPS receiver aluminium extrusion.](image)

A heat transfer fluid with anti-freeze and anti-corrosion additives is pumped through the extruded aluminium receiver spine to cool the cells and collect thermal energy. Internal fins have been incorporated in the fluid conduit to increase the heat transfer surface in order to minimise the operating temperature difference between the cells and the fluid.
The sun-tracking controller, designed at the ANU (Dennis, 2002), controls a linear actuator that is connected to a circular tracking wheel by cables. The tracking accuracy is set to ±0.2°.

5. PERFORMANCE OF THE COLLECTOR

The thermal efficiency $\eta_{th}$ and electrical efficiency $\eta_{elec}$ of the CHAPS collector are calculated based on the following definitions:

$$\eta_{th} = \frac{\dot{Q}_{th}}{\dot{G}_D \times A_m} \quad (1)$$

$$\eta_{elec} = \frac{\dot{Q}_{elec}}{\dot{G}_D \times A_m} \quad (2)$$

where $\dot{G}_D$ is the direct beam radiation and $A_m$ is the product of the mirror width and length. Figure 6 shows the efficiency results for a receiver mounted on a single mirror test rig when it is operating both with and without an electrical load. Details of the experimental apparatus and test procedure can be found in Coventry (2004). $T_f$ and $T_{amb}$ are the mean fluid temperature and ambient temperature respectively.

![Efficiency curves for the CHAPS receiver.](image)
To make a direct comparison between the efficiency curves of the CHAPS collector with those of a typical flat plate collector, it is necessary to make an assumption regarding the ratio of direct beam radiation $G_D$ to total global radiation $G_T$. Figure 7 shows a comparison between the CHAPS collector tested above (using the curve fit for thermal efficiency with concurrent electrical generation) and a Solahart Oyster Ko collector, which is a state-of-the-art flat plate solar collector with a black chrome absorber plate. There is some discrepancy between the efficiency coefficients based on aperture area from Swiss tests under the European standard EN 12975 (Solartechnik Prüfung Fororschung, 2002) and those from the Solar Rating and Certification Corporation (2000) in the US. Both results are shown. It is assumed for the sake of comparison that the direct radiation is 90% of the total radiation, which is a typical instantaneous value on a clear sunny day.

The comparison in figure 7 shows that at lower operating temperatures, a flat plate collector has a higher efficiency than the CHAPS collector, but that as the operating temperature rises, the gap in performance is reduced. Clearly the thermal losses increase more rapidly for a flat plate collector due to the larger surface area. The comparison is only valid when the two collectors are oriented directly towards the sun – a concentrating collector must track the sun, and therefore the efficiency does not suffer to the same extent as a flat plate collector due to reflection losses and cosine losses at higher incidence angles.

Under typical operating conditions and relative to the total radiation available (direct and indirect), the thermal efficiency of the CHAPS collectors is around 50% and the electrical efficiency is around 10%. Therefore, overall conversion of the available solar energy is around 60%. Because the collector tracks the sun, the amount of sunlight available over a year is increased compared to a non-tracking collector. Studies by Coventry (2004), using the solar simulation software TRNSYS, compared a 24 m long CHAPS collector with an equivalent sized Solahart flat plate array, assuming that both were linked to an appropriately sized hot water system and located in Canberra. The results show that the annual thermal output of the flat plate collector (69.9 kWh/day) is more than the CHAPS collector (55.5 kWh/day), but that if the electrical output from the CHAPS collector over the same period (19.6 kWh/day) is included, then the CHAPS collector has better overall solar utilisation. However, the electrical energy is far more valuable than the thermal energy. The economic challenge is to generate hot water and electricity from the CHAPS collector at lower cost than possible with conventional flat plate PV and solar hot water collectors.
6. TECHNICAL CHALLENGE: NON-UNIFORM ILLUMINATION

The illumination profile has little effect on the thermal performance of the receivers, but a significant impact on electrical performance. The illumination profile across a solar cell is highly non-uniform, as shown in figure 8. At near normal angles of incidence the maximum flux intensity exceeds 100 suns in localised regions.

![Figure 8. Mean flux profile cross-section on the CHAPS prototype system at 3.8° angle of incidence (left, figure from Johnston). Thermal imaging showing the temperature profile of the cover glass on a receiver (right).](image)

The high radiation flux presents a challenging environment for the materials used in the receivers. Optical components must withstand high levels of UV radiation, and the design must allow for the different rates of thermal expansion between materials. The heat sinking of the cells is important, so that their operating temperature is minimised. The efficiency of the cells is reduced by about 10% due to the non-uniform illumination flux profile across the cells. This is unavoidable unless the flux profile is evened out, for example, by the use of secondary flux modifiers located near the focal beam.

Along the length of the CHAPS collectors, the cells are connected in series in order to build up voltage and limit current, and therefore the current in each cell is the same. Because current is almost linearly dependent on the light intensity, the current in a string of identical solar cells will be limited by the one cell with the lowest illumination. For a linear concentrator such as the CHAPS system, the longitudinal radiation flux profile along the string of cells is affected by the shape of the mirror, shading due to receiver supports and gaps in the illumination due to gaps between mirrors. A typical measured flux profile along the length of a receiver is shown in figure 9.

![Figure 9. Measured radiation flux profile along the length of a receiver when the sun is at an incidence angle of 15.1°.](image)

A single cell with lower illumination than other cells in the string limits the current and performance of all cells in the series. Ensuring an even flux profile for all cells is perhaps the
largest technical challenge for the successful design of PV concentrator systems. Typically
the minimum illumination intensity is 10-20% lower than the median, depending on the
incidence angle of light.

7. CONCLUSION

An overview of current activities in solar concentrators in Australia is presented. In particular,
the Combined Heat and Power Solar (CHAPS) collector is described, and some performance
measurements are presented. It is shown that both the thermal and the electrical output
from the CHAPS collector are comparable to conventional flat plate systems. It is hoped that
the inherent advantages of a concentrator PV system - namely the reduced requirement for
costly solar cells - will lead to the production of photovoltaic power and solar hot water at a
cost lower than possible with current technologies.

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