# A solar concentrating photovoltaic / thermal collector

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# Declaration

This PhD thesis contains no material that has been accepted for the award of any other degree or diploma in any university. To the best of the author's knowledge and belief, no material previously published or written by another person has been included in this thesis, except where due reference is made in the text.

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# Abstract

This thesis discusses aspects of a novel solar concentrating photovoltaic / thermal (PV/T) collector that has been designed to produce both electricity and hot water. The motivation for the development of the Combined Heat and Power Solar (CHAPS) collector is twofold: in the short term, to produce photovoltaic power and solar hot water at a cost which is competitive with other renewable energy technologies, and in the longer term, at a cost which is lower than possible with current technologies. To the author's knowledge, the CHAPS collector is the first PV/T system using a reflective linear concentrator with a concentration ratio in the range 20-40x. The work contained in this thesis is a thorough study of all facets of the CHAPS collector, through a combination of theoretical and experimental investigation.

A theoretical discussion of the concept of 'energy value' is presented, with the aim of developing methodologies that could be used in optimisation studies to compare the value of electrical and thermal energy. Three approaches are discussed; thermodynamic methods, using second law concepts of energy usefulness; economic valuation of the hot water and electricity through levelised energy costs; and environmental valuation, based on the greenhouse gas emissions associated with the generation of hot water and electricity. It is proposed that the value of electrical energy and thermal energy is best compared using a simple ratio.

Experimental measurement of the thermal and electrical efficiency of a CHAPS receiver was carried out for a range of operating temperatures and fluid flow rates. The effectiveness of internal fins incorporated to augment heat transfer was examined. The glass surface temperature was measured using an infrared camera, to assist in the calculation of thermal losses, and to help determine the extent of radiation absorbed in the cover materials. FEA analysis, using the software package Strand7, examines the conductive heat transfer within the receiver body to obtain a temperature profile under operating conditions.

Electrical efficiency is not only affected by temperature, but by non-uniformities in the radiation flux profile. Highly non-uniform illumination across the cells was found to reduce the efficiency by about 10% relative. The radiation flux profile longitudinal to the receivers was measured by a custom-built flux scanning device. The results show significant fluctuations in the flux profile and, at worst, the minimum flux intensity is as much as 27% lower than the median. A single cell with low flux intensity limits the current and performance of all cells in series, causing a significant drop in overall output. Therefore, a detailed understanding of the causes of flux non-uniformities is essential for the design of a single-axis tracking PV trough concentrator. Simulation of the flux profile was carried out

using the ray tracing software Opticad, and good agreement was achieved between the simulated and measured results. The ray tracing allows the effect of the receiver supports, the gap between mirrors and the mirror shape imperfections to be examined individually.

A detailed analytical model simulating the CHAPS collector was developed in the TRNSYS simulation environment. The accuracy of the new component was tested against measured data, with acceptable results. A system model was created to demonstrate how sub-components of the collector, such as the insulation thickness and the conductivity of the tape bonding the cells to the receiver, can be examined as part of a long term simulation.

# Foreword

The author would like to acknowledge colleagues at CSES for their contributions to the design and production of the CHAPS system. The receiver design was modified from the air cooled system used for the Rockingham PV trough project, which is a two-axis tracking PV concentrator system designed by the ANU (Smeltink et al., 2000). The author was responsible for many of the key changes to this design, in particular, the shift to a full aluminium extrusion (with the use of anti-corrosive additives in the cooling fluid) and the inclusion of internal fins to improve the heat transfer. The design team, led by James Cotsell, assisted with realising the design and fabricating the receivers. The author was also responsible for the system design change from two-axis tracking CHAPS systems to single-axis tracking long troughs. The detailed mechanical drawings for the single axis tracking system were coordinated by John Smeltink, and the manufacturing was outsourced. The mirrors were designed by Glen Johnston and Greg Burgess, and manufactured in the solar thermal workshop at the ANU. The monocrystalline silicon solar cells were manufactured in the photovoltaic laboratory at the ANU, by a dedicated and persistent team lead by Chris Holly. The solar tracking controller was developed and built by Mike Dennis. The author carried out the experimental work to examine the impact of non-uniform light across solar cells, but would like to acknowledge the work of Evan Franklin in developing a theoretical model to further explain the results. The author would like to acknowledge the contribution by Keith Lovegrove to chapter 3, which is largely taken from a co-authored journal paper (Coventry and Lovegrove, 2003). The author carried out all data gathering and analysis in this chapter, but Keith was very helpful in discussing the intricacies of the *concept* of energy value.

The following publications were produced during the course of the research project:

**Journal papers**

Coventry, J. S. and Lovegrove, K., 2003: Development of an approach to compare the 'value' of electrical and thermal output from a domestic PV/thermal system. *Solar Energy*, **75,** 63-72.

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**Conference papers**

Coventry, J. and Lovegrove, K., 2001: Development of an approach to compare the 'value' of electrical and thermal output from a domestic PV/Thermal system. *ISES Solar World Congress*, Adelaide.

Coventry, J., 2002: Simulation of a concentrating PV/thermal collector using TRNSYS. *ANZSES Solar Energy Conference*, Newcastle.

Coventry, J., Franklin, E., and Blakers, A., 2002: Thermal and electrical performance of a concentrating PV/Thermal collector: results from the ANU CHAPS collector. *ANZSES Solar Energy Conference*, Newcastle.

Coventry, J., 2003: Performance of a Concentrating Photovoltaic/Thermal Solar Collector. *ISES Solar World Congress*, Gothenburg.

Coventry, J. S., 2003: Performance of the CHAPS collectors. *ANZSES Solar Energy Conference*, Melbourne.

Coventry, J. S., 2003: An investigation of non-uniformities in the longitudinal radiation flux profile of a single-axis tracking parabolic trough concentrator. *ANZSES Solar Energy Conference*, Melbourne.

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# Nomenclature and Abbreviations

## Nomenclature

| | |
|---|---|
| $A$ | Area |
| $A_m$ | Mirror aperture area |
| $A_s$ | Nominal cross-sectional area for the fluid conduit (excluding fins) |
| $A_{xs}$ | Cross-sectional area of the fluid conduit |
| $\dot{A}$ | Exergy (or Availability) |
| $c_p$ | Specific heat |
| $C_{p\text{-}col}$ | Thermal capacitance of the solar collector |
| $C_0$ | Capital cost |
| $C_t$ | Net cash flow generated at time t |
| $D$ | Diameter |
| $D_h$ | Hydraulic diameter |
| $FF$ | Fill factor |
| $F_H$ | Carnavos correction factor |
| $F_{dirt}$ | Scaling factor for dirt on a mirror |
| $F_{shade}$ | Scaling factor for shading of a mirror |
| $F_{shape}$ | Scaling factor for mirror shape error |
| $F_{uniformity}$ | Scaling factor to account for the effect of non-uniform radiation on electrical output |
| $g$ | Acceleration due to gravity $= 9.81\ ms^{-2}$ |
| $\dot{G}$ | Radiation flux intensity |
| $\dot{G}_T$ | Total (direct and diffuse) radiation intensity |
| $\dot{G}_d$ | Direct beam radiation flux intensity |
| $Gr$ | Grashof number |
| $h$ | Specific enthalpy |
| $h_c$ | Heat transfer coefficient for convection |

| | |
|---|---|
| $I$ | Local radiation flux intensity |
| $J$ | Current |
| $J_0$ | Dark current, or reverse saturation current |
| $J_L$ | Light generated current |
| $J_{mp}$ | Current at the maximum power point |
| $J_{SC}$ | Short circuit current |
| $k$ | Thermal conductivity |
| $k_b$ | Boltzmann's constant $= 1.381 \times 10^{-23}\ J.K^{-1}$ |
| $k_d$ | Discount rate |
| $K$ | Extinction coefficient |
| $kT/q$ | Thermal voltage = 0.02586 V (300 K) |
| $L$ | Characteristic length |
| $m$ | Mass |
| $\dot{m}$ | Mass flow of fluid |
| $n$ | Refractive index |
| $n_p$ | Lifetime of a project |
| $Nu$ | Nusselt number |
| $p$ | Pressure |
| $P$ | Perimeter of a fluid conduit |
| $P_n$ | Nominal wetted perimeter for the fluid conduit (excluding fins) |
| $Pr$ | Prandtl number |
| $q$ | Elementary charge $= 1.602 \times 10^{-19}\ C$ |
| $Q$ | Energy |
| $Q_{eq.elec}$ | Equivalent electrical energy |
| $\dot{Q}_{th}$ | Thermal output power |
| $\dot{Q}_{elec}$ | Electrical output power |
| $\dot{Q}$ | Rate of (heat) energy transfer |
| $\dot{Q}_{rad}$ | Thermal heat loss due to radiation |

| | |
|---|---|
| $\dot{Q}_{sun}$ | Solar radiation incident upon the receiver |
| $\dot{Q}_{abs-cells}$ | Radiation absorbed by the solar cells |
| $\dot{Q}_{abs-glass}$ | Radiation absorbed in the glass-silicone cover |
| $\dot{Q}'_{rad}$ | Thermal heat loss due to radiation from the glass surface |
| $\dot{Q}'_{conv}$ | Thermal heat loss due to convection loss from the glass surface |
| $\dot{Q}_{ins}$ | Thermal heat transfer through the insulation |
| $\dot{Q}''_{conv}$ | Thermal heat loss due to convection loss from the insulation cover |
| $\dot{Q}''_{rad}$ | Thermal heat loss due to radiation from the insulation cover |
| $R_{cond}$ | Thermal resistance for conduction |
| $R_{conv}$ | Thermal resistance for convection |
| $Re$ | Reynolds number |
| $R_s$ | Series resistance |
| $R_{sh}$ | Shunt resistance |
| $s$ | Specific entropy |
| $T$ | Temperature |
| $t$ | Time |
| $T_0$ | Environmental temperature |
| $T_\infty$ | Fluid temperature |
| $T_f$ | Film temperature (the average of the fluid and surface temperatures) |
| $T_s$ | Surface temperature |
| $U$ | Overall heat transfer coefficient = k/t |
| $u_m$ | Mean fluid velocity |
| $u_{wind}$ | Wind speed |

| | |
|---|---|
| $V$ | Velocity of fluid |
| $V_{cc}$ | Open circuit voltage |
| $V_{mp}$ | Voltage at the maximum power point |
| $z$ | Height |
| $\alpha$ | Absorption |
| $\alpha_H$ | Helix angle of the fins = 0 for the CHAPS receiver |
| $\beta$ | Temperature coefficient for the relationship between solar cell efficiency and temperature |
| $\delta$ | Thickness |
| $\gamma$ | Azimuth angle |
| $\Delta t$ | Small time interval |
| $\varepsilon_g$ | Emissivity of glass |
| $\eta_{pes}$ | Primary-energy saving efficiency |
| $\eta_{power}$ | Conversion efficiency of a conventional thermal power station |
| $\eta_{th}$ | Thermal efficiency |
| $\eta_{elec}$ | Electrical efficiency |
| $\theta$ | Angle of incidence of radiation |
| $\theta_{TIR}$ | Escape angle for Total Internal Reflection |
| $\theta_z$ | Zenith angle |
| $\mu$ | Dynamic viscosity |
| $\mu_w$ | Dynamic viscosity evaluated at the wall temperature |
| $\nu$ | Kinematic viscosity = $\mu/\rho$ |
| $\rho$ | Reflectivity |
| $\sigma$ | Stefan-Boltzmann constant = 5.67 x $10^{-8}$ $W.m^{-2}.K^{-4}$ |
| $(\tau\alpha)$ | Transmission-absorption product = $1 - \rho$ |
| $\tau$ | Transmissivity |

# Abbreviations

| | |
|---|---|
| *AM0* | Air Mass 0, referring to the spectral distribution of sunlight outside the atmosphere |
| *AMx* | Air Mass 1.5, referring to the spectral distribution of sunlight when the sun is at angle $\cos^{-1}(1/x)$ from vertical |
| *ANU* | Australian National University |
| *BOS* | Balance of system |
| *CHAPS* | The Combined Heat and Power Solar collector |
| *CPC* | Compound Parabolic Concentrator |
| *CSES* | Centre for Sustainable Energy Systems, at the Australian National University |
| *CSR* | Circumsolar Ratio |
| *DOE* | U.S. Department of Energy |
| *EQE* | External Quantum Efficiency |
| *FES* | Fractional Energy Saving |
| *GHG* | Greenhouse gas |
| *GOML* | Glass On Metal Laminate - the material used to fabricate CHAPS mirrors |
| *HWS* | Hot water system |
| *LEC* | Levelised energy cost |
| *LGBG* | Laser Grooved Buried Grid |
| *MPPT* | Maximum power point tracker |
| *NPV* | Net present value |
| *PT100* | Temperature sensor using a platinum resistive device |
| *PV* | Photovoltaic |
| *PV/T* | Combined Photovoltaic / Thermal |
| *SEF* | Solar Energy Fraction |
| *SHWS* | Solar hot water system |
| *SRCC* | Solar Rating and Certification Corporation |
| *TK* | Thermocouple Type K |
| *TRNSYS* | A TRaNsient SYStem simulation program, used for solar system simulations |

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