International Journal of Environmental Studies,
Vol. 63, No. 6, December 2006, 791–802

Solar thermal energy systems in Australia

KEITH LOVEGROVE AND MIKE DENNIS

Solar Thermal Group, Department of Engineering, Australian National University, Canberra, ACT 0200, Australia, keith.lovegrove@anu.edu.au

(Received 17 September 2006)

Australia has developed world leading solar thermal technologies, with only very low national market penetration. Domestic solar water heating is the most common solar thermal instrument, with around 5% of homes using it and most of these systems are conventional flat plate thermosyphon systems. Other low temperature solar thermal research includes solar crop drying, solar ponds and solar air heating but all on a small scale. There is a worldwide resurgence in interest in high temperature solar thermal through solar concentrating systems. Australia has a number of these systems many of which are near commercial fulfilment; notably, Solar Heat and Power Pty Ltd's Compact Linear Fresnel Array system currently being implemented at Liddell Power station and the ANU 400m^2 Big Dish now being commercialized by Wizard Power Pty Ltd. CSIRO has recently opened a solar energy centre in Newcastle that features a solar central receiver tower system and a trough concentrator array.

Keywords: Solar thermal energy; Water heating; Solar concentrating systems

Introduction

The sun is approximately 1.4 million km in diameter and 150 million km from the earth. It is close to 5500°C at its surface and emits radiation at a rate of 3.8×10^{23}kW. This power is supplied by nuclear fusion reactions near its core which are estimated to continue for several billion years. A tiny fraction of this energy is intercepted by the earth, but this amount is several thousand times larger than our rate of fossil fuel usage and it drives all the natural ecosystem services of the planet.

The intensity of solar radiation reaching the surface of the earth is typically between 900 and 1000 Wm^{-2} on a clear sunny day at noon. The Australian continent has the highest average amount of solar radiation per square metre per year of any continent on the planet, ranging from 1500 to 1900 kWh/m^2/yr. Australia's total current primary energy consumption of approximately 5500 PJ/a could be met by an area of 4000 km^2 of solar collectors with an average of 20% conversion efficiency. If this were constructed as a power station with 20% land coverage it would measure just 138×138 km. Alternatively, the collector area needed is close to the area of domestic house roofs available nationally.

The input of solar radiation to the biosphere is the source of energy which drives our weather systems and so in turn, wind, hydroelectric and biomass energy systems. Solar radiation can be used directly for photovoltaic energy conversion and for solar thermal conversion. Solar photovoltaic systems are discussed elsewhere in this issue.

International Journal of Environmental Studies
ISSN 0020-7233 print: ISSN 1029-0400 online
http://www.tandf.co.uk/journals
DOI: 10.1080/00207230601047156

This paper summarizes the principles and current state of research and development for solar thermal systems in Australia.

Technology overview

Various devices for collecting solar radiation thermally have been devised. At the simplest level, a flat metal plate painted black and placed in the sun will heat up until it reaches a temperature where the heat that it loses, exactly balances the amount of energy it receives from the sun. This 'stagnation temperature' occurs at around 80°C for a simple flat plate. If water, for example, is passed through passages in the plate, then it will stabilize at a lower temperature and the water will extract some of the energy. This is the essence of solar thermal energy collection.

Greater levels of sophistication aim to reduce the amount of 'thermal loss' from the collector surface at a given temperature. This allows energy to be collected more efficiently and at higher temperatures. A cover layer of glass helps by cutting down the energy lost by the circulation of cold air. If metal tubes and glass cylinders are used instead of plates, then the space can be completely evacuated, so that air convection losses are completely eliminated. Coating materials, to produce an optically selective surface that absorbs as much as possible of visible solar wavelengths whilst emitting as little as possible of thermal radiation from the plate, help to reduce radiation losses. Various combinations of these measures are used in the production of systems for solar hot water that are used around the world for domestic and industrial applications.

Further increasing the temperature at which energy can usefully be recovered, requires some method of optically concentrating the radiation so that the size of the absorbing surface, and hence its thermal loss, is reduced. The conceptually simplest approach is to employ a series of flat mirrors (called heliostats) that are continuously adjusted to direct solar radiation onto an absorbing surface elevated on a tower (a 'Central Receiver' or 'Solar Tower' system). The concept can also be adapted to linear absorbers and long strips of mirror to create a 'Linear Fresnel' concentrator.

Alternatively, the mathematical properties of a parabola can be exploited. Rays of light parallel to the axis of a mirrored parabola will all be reflected and focused at a focal point. This effect can be used in a linear arrangement, where a mirrored 'trough' with a parabolic cross section will focus solar radiation onto a line focus when it is pointed directly at the sun. Alternatively a mirrored dish with a parabolic cross section will focus solar radiation to a point focus. Both dishes and troughs require continuous adjustment of position (or at least frequent readjustment) to maintain the focus as the sun moves through the sky.

Similar focusing effects can be achieved with lenses of various kinds, but this has not been employed on the scales needed for solar thermal systems.

Another alternative which potentially avoids the need to track the sun is to employ 'non-imaging' concentration. This involves the construction of a mirrored 'light funnel' of some kind. Such a device will be able to collect rays into its aperture over a range of incidence angles and cause them to exit via a smaller aperture via multiple reflections.

Each of these approaches to concentration has a typical ratio of collected radiation intensity to incident solar radiation intensity, termed the 'concentration ratio'. Table 1 summarizes the options discussed and lists typical concentration ratios and the resultant operating temperatures that can be produced.

Table 1. Typical temperature and concentration range of the various solar thermal collector technologies.

Technology	T (°C)	Concentration ratio	Tracking
Flat plate collector	30–100	1	-
Solar pond	70–90	1	-
Solar chimney	20–80	1	-
Evacuated tube collector	90–200	1	-
Non imaging trough	90–200	2	
Linear Fresnel reflector technology	260–400	8–80	One-axis
Parabolic trough	260–400	8–80	One-axis
Heliostat field + Central receiver	500–800	600–1000	Two-axis
Dish concentrators	500–1200	800–8000	Two-axis

Low temperature systems for home and industry

Solar water heating

During the 1950s, Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) carried out world leading research into flat plate solar water heating [1]. As a result, a solar water heater manufacturing industry was established in Australia. A large proportion of the manufacturing capacity was exported. Four of the original companies are still in business and the manufacturing base has expanded to 24 companies.

Despite an excellent solar resource, the penetration of solar water heaters in the Australian domestic market is only about 5% and these sales are predominantly into new dwellings. There has been a recent surge in growth of sales of solar water heaters based on the generation of Renewable Energy Certificates (RECs) under the federal government's Mandatory Renewable Energy Target, together with additional subsidy programs offered by various state governments. The companies offering commercial systems can largely be identified from the list of certified providers of RECs on the Office of the Renewable Energy Regulator's website [2]. Rheem Australia, via its ownership of the Solahart and Edwards brands, remains the dominant manufacturer. Most companies provide very similar flat plate collector based systems for domestic hot water. Solco is notable in offering a system made from injection moulded plastic. A few commercial systems based on evacuated tube collectors are also on the market.

By collector area, a large proportion of water heater sales are unglazed pool heating units. There are a number of established manufacturers with no single manufacturer having a dominant market share.

Until recently, the domestic water heating market was dominated by flat plate systems with roof mounted tanks operating on the thermosiphon principle. Recently, pumped systems with ground mounted tanks are being offered in areas not prone to frost and evacuated tube systems are gaining popularity in cooler climates. Each of these types currently has about 7% share of the solar hot water market.

Much of the research work on solar water heaters in Australia has been carried out at the University of New South Wales (UNSW). Recently, performance studies on evacuated tube systems have been carried out. Convection models were developed for flooded evacuated tube solar collectors [3]. Mantle heat exchangers have been studied by UNSW in cooperation with the Danish Technical University as a potential solution to frost protection [4]. A further option for solar water heating in frost prone areas has led to the proposal of a falling film heat exchanger for a split system water heater [5]. This enables an existing gas storage tank to be used whereby the gas flue acts as the heat exchange surface and an antifreeze liquid can be circulated through the collectors.

At the Australian National University (ANU), variable flow strategy was tested [6] and found to give good results provided that the auxiliary heating system was disabled during the day. The author went on to describe a predictive control strategy based on weather forecasts, hot water load forecasts and the state of the storage tank. Modifications to the storage tank including an exterior auxiliary heater and variable speed pump were proposed so that the tank was auxiliary heated from the top down. Auxiliary energy costs were obtained from an Internet service and an algorithm decided on the best time to consume auxiliary energy based on cost and storage efficiency.

The University of Sydney has researched selective absorber surfaces for some time. They developed a surface treatment for evacuated tubes which is now produced in large quantities in China. Recent developments centre on ceramic/metal selective surfaces deposited using magnetron sputtering [7]. The long-term high temperature stability of these surfaces is under test.

Solar air heating

There are very few solar air heater products available in Australia. The Victorian company Sun Lizard [8], offers a box type air-heater system. T3 Energy Pty Ltd, based in the Blue Mountains in NSW, is near to commercialization of a modular system of clip together units that can be formed into roof integrated arrays, Figure 1 shows a demonstration system. The Australian National University is conducting refinement of the T3 solar air heater system.

These panels have glass covers, selective absorbers and integral air ducting. They can be configured as air only, air and photovoltaic or water only panels. The panels are coupled to a latent heat store storing up to 20kWh in the melting of a paraffin wax. Several commercial installations and two test installations are currently operating.

There was much interest in phase change salts for energy storage at the ANU in the 1980s but this work lapsed with the departure of key personnel. Recently, this group re-started

Figure 1. Commercial installation of T3E solar air heater units in Sydney.

investigations and is developing micro-encapsulated phase change materials, mainly paraffin waxes [9].

Solar air heaters have also been investigated at the University of South Australia [10]. The collector was a simple roof-integrated unit consisting of a transparent plastic sheet over blackened corrugated iron with air blown between the corrugations. It was found that the solar contribution to space heating was 38%, but 12% of the savings were offset by fan energy consumption. The same authors have conducted research into similar systems with phase change thermal storage [11]. Solid blocks of phase change material are directly coupled to air ducts in the roof cavity in such systems. They have built and tested a full-scale prototype air conditioning system with this latent storage.

Solar crop drying

Fruit, wheat and rice are all grown on a large scale in central NSW and northern Victoria. Gas-fired crop drying is widely used. Substituting solar thermal energy for gas is a logical application to investigate.

A solar assisted crop drying facility has been constructed in Griffith NSW, in collaboration with the ANU, to reduce reliance on gas for drying prunes. The energy savings due to reduce air heating by the gas furnace are potentially in the order of 60%.

A solar assisted meat drier was proposed by Fuller [12]. A similar exercise was completed by the same author on a 4000 m^2 greenhouse, heated by flat plate collectors totalling 1000 m^2. The system would have a payback of 19 years and was not pursued further. Fuller *et al.* [13] also investigated drying of chilli and beef in Bhutan using a large 73 m^2 collector and backup boiler. The system only provided a 24% solar fraction and the financial payback was found to be inadequate to justify large scale use.

Ong [14] has investigated a natural convection based crop drier and developed empirical relationships to predict its performance. The collector consisted of a simple insulated metal box painted black with a glass cover. Good agreement with experimental data was found. Such devices are proposed to dry rice.

Solar cooling

While most active cooling functions in the world are provided by mechanically driven vapour compression heat pumps, there are a number of possible technical approaches for driving cooling systems directly with a heat input. Providing the heat input from a solar thermal collector has obvious appeal for air conditioning applications where the need for cooling strongly correlates with the availability of solar radiation. Local literature is scarce. The CH2 Building in Melbourne [15] now uses latent heat stores to reduce solar cooling plant size and avoid peak energy tariffs. A solar assisted evaporative cooler is under development by the University of South Australia in partnership with the University of Kassel in Germany [16]. In this approach a strong hygroscopic salt solution dehumidifies building air which can later use evaporative cooling to provide the cooling effect. The dilute salt solution is regenerated using a solar regenerator.

Low temperature systems for power generation

Converting thermal energy to electricity via heat engine cycles is part of the process for producing most of the world's electricity at present. The second law of thermodynamics, however, predicts that the efficiency of conversion will be much higher for high temperature energy inputs. Despite this, there are a couple of approaches to power generation contemplated using low temperature inputs. In both cases the commercial argument is that very low cost collector systems are possible, offsetting the low conversion efficiency.

A very large system based on the solar chimney effect has been proposed by an Australian company [17]. The proposed project consists of 38 km^2 of clear cover suspended above a level site. Air beneath this cover will be heated to 35°C above ambient. At the centre of this giant flat plate collector a cylindrical concrete tower 1000 m high will direct the hot buoyant air upwards. The air will be used to drive adapted horizontal-axis wind turbines. A 200 MW_e chimney using 32 turbines has been proposed for a site near Mildura, NSW.

The other low temperature approach under investigation is the salt gradient solar pond. A pond of water is a highly effective collector of solar radiation, but in a normal body of water, heated water near the bottom surface, will mix by natural convection. The solar pond concept involves injecting a layer of highly saline water at the bottom of a pond. The higher density added by the salt is sufficient to overcome the density decrease that occurs as water is heated. In this way a layer of water heated by the sun can stay on the bottom of the pond in a stable non-mixing manner.

The Royal Melbourne Institute of Technology (RMIT) have an experimental 15m^2 bittern based pond on campus, commissioned in 2002 and more recently a test facility at Pyramid Hill, Northern Victoria having a capacity of 3000 m^2 and a depth of 3 m. Such ponds have been coupled to Organic Rankine Cycle power systems overseas. The RMIT group has also proposed that they be coupled to a thermal distillation unit to provide fresh water from brackish ground water [18].

Concentrating systems for high temperature processes and power generation

Concentrating solar thermal power systems use tracking mirror systems to focus radiation onto receivers that operate at the high temperatures needed for power generation. Most of the world's non renewable electricity generation is produced using steam turbine driven generators, with heat from coal or nuclear sources. Concentrating solar thermal systems have the ability to substitute for these sources and continue to utilize standard turbine generator technology.

International prospects

Solar thermal power systems via troughs, have a strong track record, with 354 MW_e of installed capacity in California, operating continuously for 20 years. Despite this there has been little growth in installed capacity. This appears set to change, with another 200 MW_e of installed capacity currently under construction around the world.

The recent success of the wind turbine industry internationally has largely been driven by demand and policy measures in favour of renewable energy in Northern European countries, notably Germany and Denmark. Solar thermal systems are not suited to the prevailing climate in those countries and also, until now, the module size of a large solar thermal power system, of between 20 and 80 MW_e has possibly been bigger than the market desired. In the last few years this situation has changed. Favourable policies in a range of locations, notably Spain, Italy, California and Nevada are now in operation. Globally the resources needed for renewable energy stations in the 10s of MW_e seem to be increasingly available.

Details on the projects currently underway can be found in [19]. These include; 'Nevada Solar 1', a 64 MW_e trough plant; 'Andasol', 2 × 50 MW_e trough plants in Spain, and the nearly completed 'PS10' 11 MW_e central receiver plant in Spain. In Australia a linear Fresnel system is being constructed adjacent to Liddell Power station, this is discussed in more detail below.

A study commissioned by the National Renewable Energy laboratory in the US [20] gives a detailed analysis of potential cost improvements for Solar Thermal Power systems, They conclude that the technology is well proven for power production and have projected market expansion and cost reductions out to 2020 and suggest deployments reaching between 5.4 GW_e and 13.6 GW_e and levelized energy costs correspondingly falling to between 3.5 USc/kWh and 6.3 USc/kWh. This is comparable to wind electricity prices.

Activity in Australia

Although we are yet to see large scale solar thermal power installations in Australia, the country is well represented in both research and development and commercialization efforts. The ANU has been active for many years. Wizard Power Pty Ltd is a new start-up company established to commercialise ANU's dish concentrator technology. Activities at the University of Sydney with support from the University of New South Wales have spun off into Solar Heat and Power Pty Ltd, which is currently building a major project at Liddell Power station in the Hunter Valley. The CSIRO Division of Energy Technology has recently opened a major solar energy centre in Newcastle that has a tower system purchased from Solar Heat and Power and a prototype trough concentrator array developed in collaboration with the ANU. The Melbourne company Solar Systems Pty Ltd, has successfully deployed dish concentrators in remote communities in outback Australia. Although these use concentrating photovoltaic receivers, the dishes are capable of high temperature operation and one was previously supplied to CSIRO for that purpose.

ANU

The ANU has worked on dish concentrator systems since the early 1970s. Early work lead to the construction of the White Cliffs solar thermal station. In 1994, the first 'Big Dish™' 400 m^2 solar concentrator (shown in figure 2), was completed on the ANU campus. Subsequently, a similar system was provided to the Ben Gurion University in Israel. In 2005, Wizard Power Pty Ltd was established by a Canberra investor in order to take the Big Dish™ technology to commercial deployment. Wizard Power has a worldwide exclusive licence to the design and associated patents, an ammonia-based thermochemical energy storage system and new advanced mirror panel technology.

The structure is based on a space-frame design with a network of tubular steel members joined to spherical nodes. The dishes rotate on reinforced concrete tracks, with a base frame supported by five bogie wheel assemblies. Triangular mirror elements are attached to the dish-frame. The mirrors used on the ANU prototype, deliver a peak concentration ratio of 1500 [21].

On the SG3 system a monotube boiler housed in a 'top-hat' cross-section cavity receiver produces steam that is superheated to typically 500°C at 4.5 MPa. This steam is passed to the ground via an insulated steam-line and rotary joints. Dish receivers of this nature can provide steam at a range of temperatures and pressures suited to commercially available steam turbines.

Figure 2. The ANU campus Big Dish prototype.

The relative merits of the dish technology and Wizard Power's plans for commercialization are discussed in [22]. Currently a joint project is underway between ANU and Wizard Power, to re-engineer the design for mass production. A Generation II prototype is due for completion by the end of 2007.

A major area of long-term interest has been the development of an energy storage system based on the reversible dissociation of ammonia, with a small laboratory scale system operated off a 20 m^2 dish system [23]. A new area of investigation for the group is solar gasification of hydrocarbons such as biomass or coal [24].

CSIRO

As noted above, the CSIRO Division of Energy Technology's new solar energy centre features a small central receiver tower system provided by Solar Heat and Power Pty Ltd [25,26].

This system uses 179 heliostats, each measuring 1.84 m × 2.44 m, to give a total area of 804 m^2. The heliostat array is a high density layout with 53% ground coverage. This has required the development of control software that is capable of guarding against accidental collisions between adjacent heliostats. The benefit is a claimed 9% increase in overall optical efficiency. The tower is 26 m high and has the capacity to incorporate a second lower receiver for operating experimental programs in parallel.

The CSIRO group will use the system as a versatile experimental test bed. An initial high priority will be a continuation of the investigation of solar reforming of natural gas to hydrogen. This work was originally carried out using a dish system at CSIRO's facility at Lucas Heights [27]. Future research goals include solar thermochemical cycles for hydrogen production [28].

The CSIRO Energy Centre also features a trough concentrator array that was constructed in collaboration with the ANU Solar Thermal Group [29]. It consists of four rows of 18 mirrors each with a total aperture area of approximately 132 m^2. The array is a prototype of systems capable of providing process heat in the 200–300°C temperature range. Current plans are to use the trough array to test a small Organic Rankine Cycle power system and also an absorption chiller for air-conditioning applications.

The mirror panels are an improved version of those used on the demonstration concentrating photovoltaic 'Combined Heat and Power System' at ANU [30,31]. The reflective surface of the mirror panels is a Glass On Metal Laminate (GOML) which has been elastically deformed to a parabolic profile. The mirrors are low iron, back silvered 1mm drawn glass, with a reflectivity of 94%. Simple glass shielded tubular receiver units are used and thermal heat transfer oil will be used to transfer heat to a $6kW_e$ organic Rankine cycle turbine provided by Freepower [32] will be tested with a nominal 240^oC 80 kW_{th} input.

Solar Heat and Power Pty Ltd

The CSIRO tower, is a prototype single tower from what Solar Heat and Power Pty Ltd have proposed as 'Multi Tower Solar Arrays' (MTSA) [33]. In addition to this, the company have been working for several years on a variation of a linear Fresnel concept, the 'Compact Linear Fresnel Reflector' (CLFR) system [34,35]. The concept was originally developed at the University of Sydney and then taken into the commercial arena by Solar Heat and Power. One of the unique features employed in both MTSA and CLFR approaches, that differentiates it from the standard Fresnel or tower approach, is the idea that, in a close packed array of heliostats, with adjacent parallel tower receivers, optical efficiency will be improved if some of the heliostats can be alternated to point at different receivers and that this alternating pattern can be varied in an optimum way as the sun moves during the day [36].

Their current research and development program is centred on tests with a 40 MW_{th} CLFR system at Liddell power station in the Hunter Valley. Stage 2 of this project is currently under construction and will comprise 20,000 m^2 of collector producing high temperature pressurized water that will be used via a heat exchanger, to pre-heat feedwater at the coal fired power station. Based on the conversion efficiency of the existing coal plant, a planned equivalent generating capacity of 5 MW_e is claimed. The Fresnel mirrors in the stage 2 system are

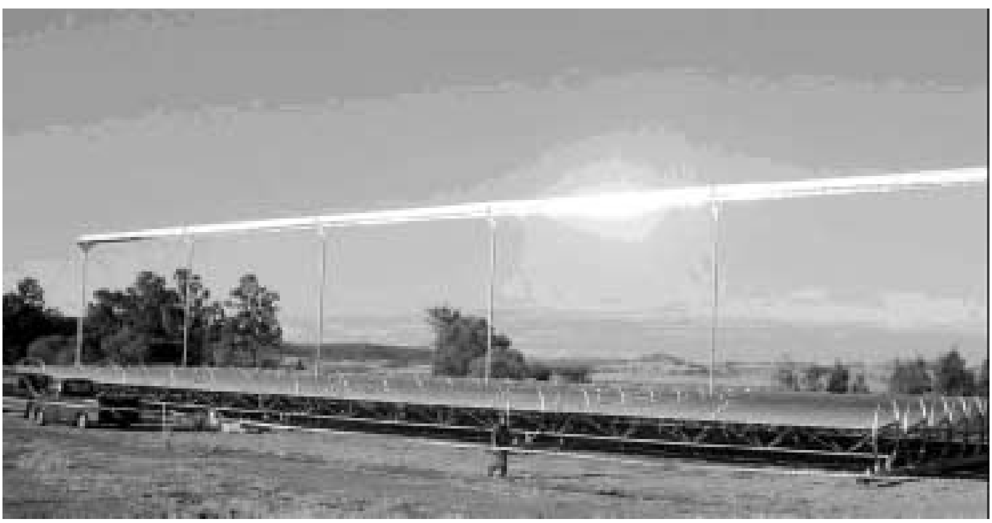

Figure 3. Stage 1 of the Solar Heat and Power Pty Ltd, Liddell CLFR array in operation (picture from Mills *et al.*, 2006 [34]).

2.25 m wide. A view of their stage 1 test loop is shown in figure 3. The mirrors are formed from elastically curved glass glued to lateral sheet steel ribs which in turn are supported on a truss structure, supported at the ends on circular hoops on rollers.

The more favourable policy environment in Europe has motivated the company to look to Portugal for a first standalone plant. A joint venture has been formed and a 6.5 MWe trial standalone plant planned. The standalone plant will use saturated steam at 280°C. Solar Heat and Power have discussed the advantages of energy storage for solar thermal power plants and mooted the idea of storage of high pressure high temperature water in underground caverns.

Solar Systems

Solar Systems is a Melbourne-based company that has successfully commercialized dish concentrators. Although their product is designed as a concentrating photovoltaic system, the dish could in principle be used as a high temperature thermal system. Solar Systems, provided the dish unit used by CSIRO in previous investigations of solar reforming of natural gas.

The Solar Systems dish is 130 m^2 and achieves a 468 times concentration ratio onto photovoltaic receivers. An optical efficiency of 85% is claimed which when combined with receiver efficiency of 30% gives and overall 20% system efficiency. In the last eight years, the company has installed systems to a combined capacity of 1 MW_e in communities in outback Australia [37].

Other players

Yeomans Plow company based on the Gold Coast [38] have built a prototype of an interesting floating Fresnel concentrator. It consists of a series of 5 m^2 concrete flotation modules on a pond of water. Each module has strips of low-iron glass mirrors in a linear Fresnel arrangement set into the top surface. The floating modules track the sun in azimuth by being rotated within the pond.

A group called Project Sierra have made a novel use of inflated clear plastic spheres which house stretched membrane front surface plastic mirrors. These spheres float in small base frames filled with water and can roll in arbitrary directions for tracking. The units could act as heliostats or individual fixed focus dish units. Little progress has been reported so far.

There are no doubt other individuals and companies who are attracted to the apparent benefits of concentrator technology and are considering possible implementations.

Conclusion

A range of proven technologies exist for exploiting solar thermal energy input over temperatures ranging from 30°C to several 1000°C. Australia possesses the highest average solar radiation resource of any of the world's continents. In principle, we could meet all our primary energy needs through solar thermal technologies, using an area comparable to our existing roof area.

Australia led the world in the development of solar water heaters in the 1960s. Although we have many companies now offering commercial products, the market penetration of 5% is low.

Trough, Fresnel, Tower and Dish Concentrator technologies offer routes to the higher temperatures needed for efficient power generation, industrial heat, chemical processes and fuels production. There is a resurgence of interest worldwide in these technologies and a period of rapid growth seems to be beginning.

Australia is well represented in R&D and commercialization of all solar thermal technologies, but the market signals are not as good as they are overseas. There is a risk that the country could lose the benefits of this new growth industry.

References

[1] Morse, R., 1961, Water heating by solar energy, CSIRO Division of Mechanical Engineering technical report, Commonwealth Scientific and Industrial Research Organisation, Highett, Melbourne.

[2] ORER website: www.orer.gov.au/ (accessed July 2006).

[3] Budihardjo, I., Morrison, G. and Behnia, N., 2005, A study of natural circulation flow rate through single ended evacuated tube solar collectors. Proceedings of the International Solar Energy Society Solar World Congress, Orlando, FL.

[4] Soo Too, Y., Morrison, G. and Behnia, N., 2005, Heat transfer and flow visualisation in vertical mantle heat exchangers for solar water heaters. 6th World Conference on ExHFT, Matshushima, Miyagi, Japan.

[5] Soo Too, Y. and Morrison, G., 2006, Falling film heat exchangers for solar water heaters. Proceedings of Australian and New Zealand Solar Energy Society annual conference, Solar 2006, Canberra, 13–15 September.

[6] Dennis, M., 2004, Active control of domestic solar water heaters. PhD Thesis, Department of Engineering, Australian National University, ACT 0200.

[7] Bosi, S., Bittar, A., Zhang, Q.-C. and Mills, D., 2001, Age testing of solar selective surfaces on flat plates at 150ˆC and 300ˆC in air. Proceedings of the International Solar Energy Society World Congress, Adelaide, SA.

[8] Sun Lizard, www.sunlizard.com.au (accessed July 2006).

[9] Dennis, M. and Brownrigg, W., 2006, Micro-encapsulation of phase change materials. Annual conference of the Australian & New Zealand Solar Energy Society, Solar 2006, Canberra, 13–15 September.

[10] Belusko, M., Saman, W. and Bruno, F., 2003, Development of a low cost solar heating system. Preprints of the 2003 International Solar Energy Society, Göteborg, Sweden.

[11] Belusko, M., Saman, W. and Bruno, F., 2004, A roof integrated solar heating system with glazed collector. *Solar Energy,* **76,** 61–69.

[12] Fuller, R., 2001, Solar drying in Australia: a historical review. Proceedings of the International Solar Energy Society conference, Adelaide, 2001.

[13] Fuller, R., Lhendup, H. and Aye, L., 2005, Technical and financial evaluation of a solar dryer in Bhutan. Annual conference of the Australian & New Zealand Solar Energy Society, Dunedin, New Zealand.

[14] Ong, K., 1995, Thermal performance of solar air heaters: mathematical model and solution procedure. *Solar Energy,* **55,** 93–109.

[15] Aye, L. and Fuller, R., 2005, The proposed heating and cooling system in the CH2 building and its impact on occupant productivity. *The Australian Journal of Construction Economics and Building,* **5**(2).

[16] Krause, M., Saman, W. and Vajen, K., 2005, Open cycle liquid dessicant air conditioning systems. Annual conference of the Australian & New Zealand Solar Energy Society, 2005.

[17] Enviromission, www.enviromission.com.au (accessed July 2006).

[18] Akbarzadeh, A. and Andrews, A., 2005, Integration of solar ponds in salinity mitigation schemes to produce low grade heat for industrial process heating, desalination and power. Proceedings of International Solar Energy Society Solar World Congress, Orlando, FL.

[19] SolarPACES, 2006, *Proceedings of the 13th International Symposium on Concentrating Solar Power and Chemical Energy Technologies,* 20 June, Seville, Spain, ISBN 84-7834-519-1.

[20] Sargent and Lundy Consulting Group, 2003, Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts. National Renewable Energy Laboratory, report NREL/SR-550-34440.

[21] Johnston, G., 1995, Flux mapping the 400 m2 ‘Big-Dish’ at the Australian National University. *ASME Journal of Solar Energy Engineering,* **117,** 290–292.

[22] Lovegrove, K., Zawadski, A. and Coventy, J., 2006, Taking the ANU Big Dish to commercialization. Proceedings of ANZSES annual conference, Solar 2006, Canberra, 13–15 September.

[23] Lovegrove, K., Luzzi, A. and Kreetz, H., 1999, A solar driven ammonia based thermochemical energy storage system. *Solar Energy,* **67**(4–6), 309–316.

[24] Munzinger, M. and Lovegrove, K., 2006, Biomass gasification using solar thermal energy. Proceedings of ANZSES annual conference, Solar 2006, Canberra, 13–15 September.

[25] Stein, W., Imenes, A., Hinkley, J., Benito, R., McEvoy, S., Hart, J., McGregor, J., Chensee, M., Wong, K., Wong, J. and Bolling, R., 2006, A new solar thermal facility in Australia. *Proceedings of the 13th International Symposium on Concentrating Solar Power and Chemical Energy Technologies,* 20 June, Seville, Spain, ISBN 84-7834-519-1.

[26] Schramek, P., Mills, D.R., Stein, W. and LeLievre, P., 2006, Design of heliostat field of the CSIRO solar tower. *Proceedings of the 13th International Symposium on Concentrating Solar Power and Chemical Energy Technologies,* 20 June, Seville, Spain, ISBN 84-7834-519-1.

[27] Edwards, J.H., Do, K.T., Maitra, A.M., Schuck, S., Fok, W. and Stein, W., 1996, The use of solar based CO2/CH4 reforming for reducing greenhouse gas emissions during the generation of electricity and process heat. *Energy Convers. Manag.,* **37,** 1339–1344.

[28] Hinkley, J., Duffy, G., Edwards, A. and Stein, W., 2006, Sulphur based thermochemical cycles for solar hydrogen production. *Proceedings of the 13th International Symposium on Concentrating Solar Power and Chemical Energy Technologies,* 20 June, Seville, Spain, ISBN 84-7834-519-1.

[29] Kohlenbach, P., McEvoy, S., Stein, S., Burton, A., Wong, K., Lovegrove, K., Burgess, G., Joe, W. and Coventry, J., 2006, A new parabolic trough solar collector. Proceedings of ANZSES annual conference, Solar 2006, Canberra, 13–15 September.

[30] Coventry, J., Franklin, E. and Blakers, A., 2002, Thermal and electrical performance of a concentrating PV/Thermal collector: results from the ANU CHAPS collector. Annual conference of the Australian & New Zealand Solar Energy Society, Newcastle, New South Wales, November.

[31] Coventry, J., 2005, Performance of a concentrating photovoltaic/thermal solar collector. *Solar Energy,* **78**(2), 211–222.

[32] Freepower, http://www.freepower.co.uk/ (accessed July 2006).

[33] Schramek, P. and Mills, D.R., 2003, Multi-tower solar array. *Solar Energy,* **75,** 249–260.

[34] Mills, D.R., Le Lièvre, P., Morrison, G. and Millioud, A., 2006, Compact linear Fresnel reflector progress. *Proceedings of the 13th International Symposium on Concentrating Solar Power and Chemical Energy Technologies,* 20 June, Seville, Spain, ISBN 84-7834-519-1.

[35] Mills, D.R., Morrison, G.L., Pye, J. and Le Lievre, P., 2006, Multi-tower line focus fresnel array project. *Journal of Solar Energy Engineering, Transactions of the ASME,* **128,** 118–121.

[36] Schramek, P. and Mills, D.R., 2004, Heliostats for maximum ground coverage. *Energy,* **29**(5–6), 701–713.

[37] Lasich, J., 2006, Address given at 13th International Symposium on Concentrating Solar Power and Chemical Energy Technologies, 20 June, Seville, Spain.

[38] Yeomans, www.yeomansplow.com.au/ (accessed July 2006).