

Advances in solar thermal electricity technology

D. Mills

Department of Applied Physics, University of Sydney, Sydney, Australia

Abstract

Various advanced solar thermal electricity technologies are reviewed with an emphasis on new technology and new market approaches.

In single-axis tracking technology, the conventional parabolic trough collector is the mainstream established technology and is under continued development but is soon to face competition from two linear Fresnel reflector (LFR) technologies, the CLFR and Solarmundo. A Solarmundo prototype has been built in Belgium, and a CLFR prototype is awaiting presale of electricity as a commercial plant before it can be constructed in Queensland. In two-axis tracking technologies, dish/Stirling technologies are faced with high Stirling engine costs and emphasis may shift to solarised gas micro-turbines, which are adapted from the small stationary gas turbine market and will be available shortly at a price in the US\$1 ppW range. ANU dish technology, in which steam is collected across the field and run through large steam turbines, has not been commercialised. Emphasis in solar thermal electricity applications in two-axis tracking systems seems to be shifting to tower technology. Two central receiver towers are planned for Spain, and one for Israel. Our own multi-tower solar array (MTSA) technology has gained Australian Research Council funding for an initial single tower prototype in Australia of approximately 150 kW(e) and will use combined microturbine and PV receivers. Non-tracking systems are described of two diverse types, Chimney and evacuated tubes. Solar chimney technology is being proposed for Australia based upon German technology. Air is heated underneath a large glass structure of about 5 km in diameter, and passes up a large chimney through a wind turbine near the base as it rises. A company Enviromission Ltd. has been listed in Australia to commercialise the concept. Evacuated tubes are growing rapidly for domestic hot water heating in Europe and organic rankine cycle engines such as the Freepower 6 kW are being considered for operation with thermal energy developed by evacuated tube and trough systems. These may replace some PV in medium sized applications as they offer potential for inexpensive pressurised water storage for 24 h operation, and backup by fuels instead of generators. In the medium term there is a clear trend to creation of smaller sized systems which can operate on a retail electricity cost offset basis near urban and industrial installations. In the longer term large low cost plants will be necessary for large scale electricity and fuels production. Retrofit central generation solar plants offer a cost effective transition market which allows increased production rates and gradual cost reduction for large solar thermal plant. In the paper the author describes current funding systems in Europe, Australia, and the USA, and makes suggestions for more effective programmes of support.

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1. Introduction

Solar thermal electricity may be defined as the result of a process by which directly collected solar energy is converted to electricity through the use of some sort of heat to electricity conversion device. Mostly this is a

heat engine, but there are other options such as a thermoelectric pile converter or a fan converter as in solar chimneys.

Solar thermal electricity on grid was not achieved until the 1980s, although the basic technology for the production of mechanical energy (which could be converted to electricity using a conventional generator) had been under development for about 140 years, beginning with Mouchot and Pifre (Pifre, 1882) in France, and continued by extraordinary pioneers such as Ericsson

E-mail address: d.mills@physics.usyd.edu.au (D. Mills).

(1888), Eneas (1901), Shuman (1913), and Francia (1961, 1968). In the 1980s, the first large trough, dish and tower arrays were installed in response to the challenges of the 1970s oil crises, and one of these, the Luz LS3 trough collector technology, was installed in several large successful 80 MW arrays. These are still operating.

Solar thermal power has probably the greatest potential of any single renewable energy area, but has been delayed in market development since the 1980s because of market resistance to large plant sizes and poor political and financial support from incentive programmes. However, at this time there is rapid development occurring both in the basic technology and the market strategy, and prospects for rapid growth appear now to be very bright for newer approaches.

In this paper, an overview of the current technologies which are available, or are being developed, is given together with an assessment of their market prospects. There will be a stress on new developments and technologies. Our group is active in fixed collectors and both basic types of tracking strategy development. I will describe our own approaches in some detail but will also stress the most recent activity of other groups.

2. Single axis tracking technologies

This category is comprised of technologies in which relatively long and narrow reflectors are tracked about a single axis to keep the sun's image in focus on a linear absorber or receiver. The receiver is normally a tube or series of tubes which contain a heat transfer fluid.

2.1. Parabolic trough technology

This technology uses reflectors curved around one axis using a linear parabolic shape, which has the property of collecting parallel rays along a single line focus and nearly parallel rays from the solar beam in a line image. A long pipe receiver can be placed at the focus for heating of heat transfer fluid.

In 1984, the first SEGS (solar electric generating systems) plant was installed in southern California by LUZ International, Inc. These plants (Frier and Cable, 1999) utilize single-axis parabolic trough reflectors that track the Sun with a north–south axis of rotation. Optical concentration of between 19:1 (LS-1) and 26:1 (LS-3) reduces radiative losses to a few percent, but this concentration factor also limits the collection of diffuse radiation to very insignificant levels. LS-1 and LS-2 used black chrome selective coatings but these were succeeded in the LS-3 series using metal ceramic coatings which allowed efficient operation at 391 °C. This is still the current model at the time of writing, although the absorbing surface has been improved. A north–south

tracking axis orientation gives a high summer bias to annual electricity output, which is useful in California. Superheating is carried out using natural gas. Hybrid solar/fossil operation soon showed itself to be more cost-effective and reliable at supplying peak loads than limited storage could be, but the gas usage was limited to 25% by Federal laws which were related to plant subsidies received.

While a huge improvement on what went before, the LS-3 designs are currently not market-competitive without a substantial environmental compensation subsidy. However, the current industrial groups backing the technology believe that the next major improvements in their technology would, in large production, result in electricity generation costs of US\$0.055/kWh in areas of high insolation. Cost reduction can take place both through larger scale production and design improvements.

In the latter area, considerable work is being undertaken to reduce structural cost, and the Eurotrough Project has developed a cheaper box section support system for the trough reflectors (Geyer et al., 2001). DSG would also make an important cost and performance improvement in the cost of commercial plant but the process has proved difficult because the tilting trough for some of the time illuminates the top of the absorber tube containing vapour phase, which is poorly conductive. This can cause stratification of flow, tube overheating and pipe bending under the temperature differences which arise across the pipe cross-section.

Since 1989, work has been proceeding on direct steam generation (DSG) in a much modified version of the technology called LS-4, and although this work was much interrupted during the 1990s by corporate reorganization. In a larger effort by the German DLR, the “Direct Steam Generation In Parabolic Troughs” (DISS) project (Zarza et al., 1999) at the Plataforma Solar de Almeria (PSA) site is working on the same problem in a horizontal trough system; they have recently abandoned tilted troughs (Zarza et al., 2001) as difficult to market and unnecessary to achieve DSG. The DISS project has tried three DSG concepts and has come out in favour of the “recirculation” concept in which liquid is circulated in an evaporating portion of the array at saturated steam conditions, and steam is taken off with a steam separator to a separate part of the array for superheating. Recirculating the liquid increases parasitic energy costs but the system has good controllability of superheated steam parameters and stratification is impossible in the evaporator. The project is turning to demonstration of parallel row operation.

With 354 MW of installed capacity, parabolic troughs represent the most mature solar thermal electricity technology. To date, there are more than 100-plant years of experience from nine operating plants, which range in size from 14 to 80 MW. The nine plants



Fig. 1. A portion of an LS-3 plant at Kramer Junction, California.

are located at three sites in the Mojave Desert near Barstow, California: Daggett (SEGS I and II), Kramer Junction (SEGS III through VII) (Fig. 1), and Harper Lake (SEGS VIII and IX). The Kramer Junction site has achieved a 30% reduction in operation and maintenance (O&M) costs during the last 5 years. This reduction is the result of major improvement programs for the collector design and the O&M procedures.

No new plants have been built since 1991 because declining fossil-fuel prices and relatively restricted incentives for large solar plants. New plants, using current technology with these proven enhancements, could produce power today for about US\$0.10–0.12/kWh. With an environmental subsidy based upon carbon trading, a World Bank funded study (Enermodal Engineering Ltd., 1999) suggests that in large production this technology would be competitive against fossil fuel, with the cost of electricity under a US\$25 per tonne carbon credit between US\$0.032 and \$0.043/kWh, lower than conventional generation. This does not include any local environmental improvement which might be valued.

Trough collectors now have competitors arising in the new LFR and CLFR plants described in the next section, and it will be interesting to see whether they can withstand this potentially low cost competition.

2.2. Linear Fresnel reflector technologies

This is a single axis tracking technology but differs from a parabolic trough in that the absorber is fixed in space above the mirror field and the reflector is composed of many long row segments which focus collectively on an elevated long tower receiver running parallel to the reflector rotational axis. The first such array was a small one built by Francia (1961), but since then little was done until the last few years when development began on two LFR designs in Australia and Belgium.

Both the CLFR and the Solarmundo seem set to offer generation costs below current trough plant in both short and long term.

2.2.1. Compact linear Fresnel reflector (CLFR)

Development began on this Australian design at the University of Sydney in 1993 and it was patented in 1995. Initial interest from Solel at this time disappeared after financial problems within that company, but interest rose within the Australian utility industry and Austa Energy and Stanwell Corporation agreed to develop a plant under the Australian Greenhouse Renewable Energy Showcase scheme in 1999, with the reflector field to be constructed by Solahart International. Unfortunately, the Austa group was abolished shortly after and their developmental expertise was lost to the project.

Since 1999 progress has been slow but steady technically (Mills and Morrison, 1999) and a very efficient and simple design has been evolved now using an advanced cavity receiver, but the criteria for commercial plants have become very difficult in Australia due in part to very low penalty clauses introduced into the 2010 renewable energy obligation legislation. This means that the initial project sub-array has been halted, waiting for a buyer at a green power price more than double the penalty price. A cost of A\$0.12 (US\$0.06) per kWh(e) is calculated over 20 years for the first 50 MW(e) feedwater preheat plant in Rockhampton and about US\$0.055 for the first 100 MW(e) plant, both including 11% profit. Cost will drop further in large production, or if steam can be supplied to the main boiler, where the thermodynamic efficiency of conversion is higher.

This CLFR is not a classical LFR because it employs a strategy based upon multiple towers which allows area coverage to be significantly reduced by partially inter-meshing two adjacent single tower arrays. It also makes significant optical efficiency advances around the tower, which uses a flat cavity receiver attached to boiling tubes. No secondary reflector is used in order to maintain high optical efficiency and avoid the use of hot reflectors. The absorber is free to move at one end under thermal expansion. The reflector rows are 200 m long and 1.6 m wide, and composed of modules 6 m long (see Fig. 2). The reflectors are slightly curved to achieve a fine focus. The row pulled by a centre mounted motor, and employs a separate braking system. The reflectors are made of thin glass glued to a metal backing. They are curved very slightly and have a reflectance 0.95. This design has particular advantages with direct boiling, because the boiling tubes always have a water interface inside where it is illuminated on the tube underside. This allows the system to operate under a wide variety of boiling regimes, including stratified flow avoided by parabolic troughs.

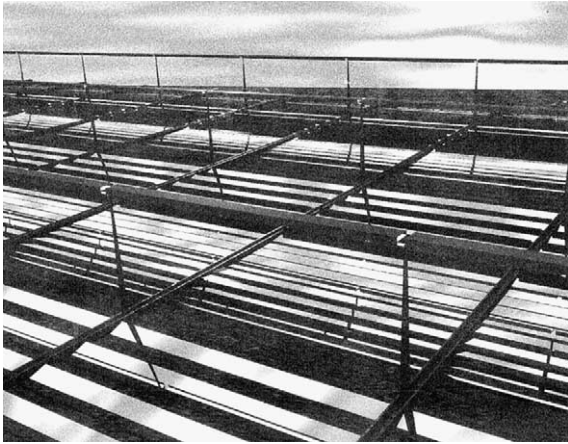


Fig. 2. Visualisation of an early version of the CLFR with a cavity receiver. The reflector rows are now centre pulled in a row length of 200 m without the visual break of cross supports, and the cavity receiver has been altered.

The CLFR is calculated by our group to deliver tracked beam to electricity efficiency of 19% on an annual basis as a preheater. The peak power per km^2 of collector will be 228 MW(e) and the peak power per km^2 of ground area is about 160 MW(e). There is a substantial potential market for retrofit addition to fossil fuelled plant in southern Europe which may of the order of 500 MW(e). For addressing the even larger main boiler supplementation market, the design can use high temperature air stable selective coatings now under development in Europe, the USA, and Australia.

2.2.2. Solarmundo

Solarmundo (2001) was formed and this LFR design was initiated in 1997 after some of the former Solel participants had become familiar with the Sydney

work in 1995. However, there are important differences between the two designs and the Solarmundo has proceeded more quickly to prototype status. The Solarmundo is a more classical LFR which does not employ intermeshed single tower arrays like the CLFR, and it has a relatively higher tower/field width ratio. A $100\text{ m} \times 26\text{ m}$ prototype has been tested in Belgium, and the technology is now on the market awaiting the first project customer. Like the CLFR, it uses a cavity receiver, but unlike the CLFR it uses a reflector inside the cavity and a single tubular absorber. This requires the use of a glass secondary reflector operating at elevated temperatures. According to presentations given by the company, the absorber is a selectively coated non-evacuated tube behind a glass tube, and the design is intended to use new stable absorber coatings under development in Europe. The prototype used a glass primary reflector but promotional material mentions a front surface reflector about which no information is given. The absorber is free to move under thermal expansion, being contained by a light U-shaped tower structure and moving supports (Fig. 3).

The Solarmundo LFR is said by the company to deliver beam to electricity efficiency between 10% and 12% on an annual basis, compared to between 14% and 16% for a trough collector. The peak power per km^2 of collector is 111 MW(e) and the peak power per km^2 of ground area is unavailable. A cost of 10.4 Eurocents per kWh(e) is stated in promotional literature for a 50 MW(e) plant in southern Spain, and 7.5 Eurocents in Egypt. The design was launched this October and is available for investors to develop to commercial status.

2.3. Solar roof

Duke Solar in the United States are commercialising solar roof technology in which a single axis tracking moving absorber stationary reflector system provides

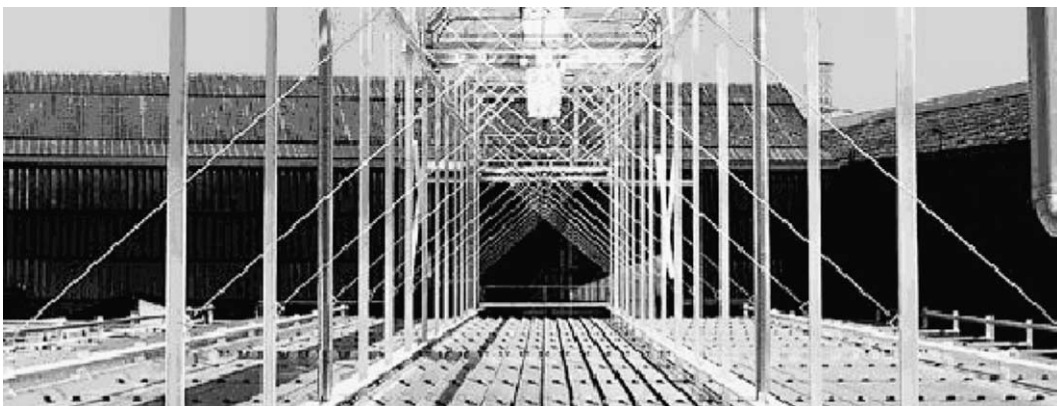


Fig. 3. A photo of the first Solarmundo trough with inverted “U”-shaped towers.

combined heat and power (CHP) to individual large buildings as a roof integrated system. The Power Roof™ system includes features of a high-temperature solar collector, a natural daylighting system, a radiant barrier, an insulating system, an optional means to capture passive solar heat in the winter, an infiltration barrier, the building roof structure, and a waterproof, guaranteed roofing system. Collection temperatures up to more than 400 °C are claimed. Collected thermal energy can subsequently be utilized for industrial processes, double-effect absorption cooling, desalination and water purification as well as secondary space heating and domestic hot water uses.

3. Two axis tracking technologies

3.1. Paraboloidal dishes

3.1.1. SG3 ANU dish

The Australian National University (ANU) paraboloidal dish technology (Fig. 4) has been available for some time as a potential array technology in which steam is collected across the field and run through large steam turbines, but no commercial array of this type has yet been constructed. The 25 m diameter SG3 dish is hexagonal in shape and formed of 54 triangular mirror panels composed of thin glass mirror backed by a foam and metal laminate developed by ANU. The focal length is 13.1 m. The dish has a back frame which allows changes in elevation, and a base frame which allows azimuthal movement around a track. Emphasis has been on development of a lightweight, very stiff structure. Two have been built so far, one in Canberra and one which has been sent to Israel to be used as a test bed for the Weizmann Institute. The second dish, called PETAL, has been installed for high concentration experiments, and is apparently operating well.



Fig. 4. The ANU SG3 dish installed at Sede Boqer in Israel as the PETAL.

3.1.2. Boeing SES dish

Most other dish designs are linked to the use of Stirling Cycle motors. In the United States, Phase II of the Boeing/Stirling Energy Systems Dish Engine Critical Components (DECC) project (Fig. 5) began in October 2000 and is aimed at producing two advanced systems by the end of 2001.

The project so far has delivered 10 000 h of operation on sun with an average daily conversion of solar beam to electricity of 24%, a peak efficiency of 29.4%, a peak solar power generation of 24.9 kW and a solar availability of 96%. The engine is a Kockums 4-95 Kinematic Stirling engine which operates at 720 °C. The next stage in the project will be to conduct extensive field trials, possibly in the south west of the United States.

A second USA project is the 30 kW SAIC/STM joint venture (Fig. 6) which uses an SAIC dish and an STM generation III 4-120 kinematic stirling engine operating at 720 °C. The annual solar efficiency achieved so far is 18% and the peak 23%. The dish engine can be operated using natural gas. Two dishes have been built and are in Golden, Colorado and Phoenix, Arizona.

In Europe, SBP and DLR (Deutsches Zentrum fuer Luft- und Raumfahrt e.V.) have been running three DISTAL I systems with a rated power of 9 kW at the Plataforma Solar de Almería (PSA) in Spain for more than 20 000 h with 90% availability. They have achieved an effective radiant flux concentration of more than 3500 and a peak solar-to-electric conversion efficiency of more than 20%. In a European Union (EU) project the DLR is developing and testing a hybrid version of the heat pipe receiver with an integrated gas burner. A new 8.5 m diameter DISTAL II dish of higher concentration is under test. This has fully automatic sunrise-to-sunset tracking operation and uses a re-worked SOLO 161 Stirling engine. These technologies



Fig. 5. The current Boeing/SES dish/stirling design. Photo from <http://www.energylan.sandia.gov/sunlab/PDFs/boeing.pdf>.

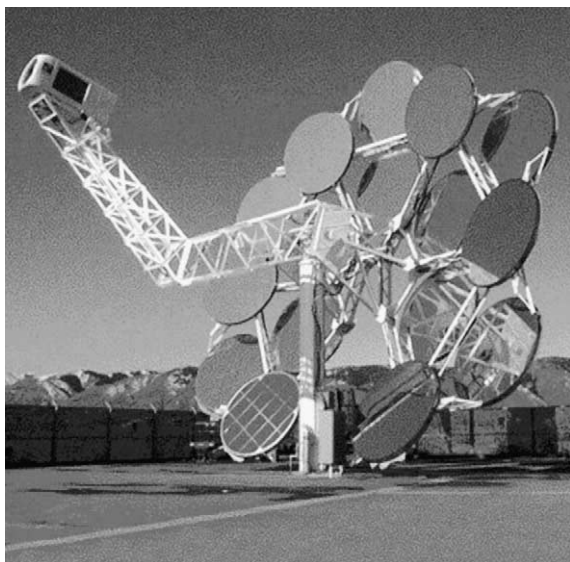


Fig. 6. The current SAIC/STM dish system. More information can be obtained at <http://www.energylan.sandia.gov/sunlab/PDFs/usjvp.pdf>.

are not yet commercialised. The SOLO engine has also been used in a Dish project in the USA involving the University of Las Vegas.

Dish-Stirling technologies are currently faced with high Stirling engine costs (figures are difficult to come by but a cost over US\$7 ppW seems likely) and emphasis may shift shortly to solarised Brayton micro-turbines, which are adapted from the small stationary gas turbine market and will be available shortly at a price in the US\$1 ppW range. The lower Brayton costs are due to high production quantities in the stationary market. The efficiency of the Braytons, at 25–33%, is lower than the 42% of the best Stirlings, but cost-efficiency may be improved using the former. However, larger Braytons may have peak efficiency close to 40% (Romero et al., 1999) but these are too large for dishes.

Further competition may arise from PV receivers like the 34% GaAs tandem cell recently announced by a Boeing subsidiary, Spectrolab (Refocus magazine, 2001). It is claimed that this cell could be produced at \$1 ppW in MW quantities, based upon a 400× concentration factor. Clearly, this cell type could be used with the Boeing dish and deliver an efficiency in the range of current dish/Stirling systems.

3.2. Single tower—central generation

Solar tower technology has been dominated by the central receiver concept involving a single large tower.

Early plants included small prototype built by Francia in the 1960s in Genoa (Francia, 1968), included the 750 kW(e) Eurelios plant in Adrano, Sicily operating

at 512 °C using water/steam HTF and eutectic salt storage in 1981 (the first CR to be grid connected), a 500 kW(e) plant in Almeria, Spain, operating at 530 °C using sodium HTF and sodium heat storage (1981), an 800 kW(e) plant in Nio, Japan operating at 249 °C using water/steam HTF (1981), the 2.3 MW(e) Themis plant in Targassonne, France, operating at 450 °C using salt heat transfer fluid (HTF) and a two-tank molten salt heat storage (1982), which achieved a net peak solar beam to electric efficiency of 17%. The 11.7 MW(e) “Solar One” at Barstow in California (see Fig. 7), operating at 510 °C using water/steam and oil storage at 302 °C peak (1982) which achieved a net peak solar beam to electric efficiency of 8.7%, and a net average annual solar beam to electric efficiency of 5.8%, and a 5 MW(e) “SES-5” in the Crimea, USSR, operating at 256 °C using water and saturated steam HTF and pressurized water storage (1985). Solar One was converted to Solar Two in the 1990s using molten salt heat transfer. Both the Solar Two and Themis plants successfully demonstrated molten salt storage, allowing the solar plant to deliver electricity during the evening or in cloudy periods.

Two more advanced commercial central receiver tower projects are planned for Spain, the 10 MW PS10 and the 15 MW Solar Tres. These projects are dependent upon ratification by the Spanish Government of the 1999 Solar Decree, which would guarantee about US\$0.19/kWh for solar generation. The decree does not apply to solar/fossil hybrids below 50% solar fraction and therefore encourages the use of some storage, which both projects include.

Solar Tres is, as the name implies, a direct descendent of the Solar Two molten salt tower technology. This is aimed a central generation of dispatchable electricity to



Fig. 7. The Solar Two central receiver plant in Barstow, California. This plant is now shut down but the next is under development for Spain as Solar Tres.



Fig. 8. A Spanish designed heliostat, of the type to be used in the PS10 tower project, being cleaned.

the Spanish grid, day or night. The peak power is only 1.5 times higher than for Solar Two, but the field will be much larger because of the incorporation of a 16 h full power storage requirement. Molten nitrate salt is used as both the heat transfer fluid and the storage medium, and flows through pipes illuminated by the sun at the top of the tower. The conventional Rankine cycle turbine is provided with steam at a temperature close to the peak salt temperature of 565 °C.

The PS10 is a 10 MW tower system being developed in Spain but has a close relationship to the previous Phoebus technology (see Fig. 8). The consortium includes CIEMAT, DLR, FICHTNER and will be run by an IPP called Sanlucar Solar. This tower (Romero, 2001) will use a volumetric air receiver operating at 680 °C at the top of a 90 m tower, and a conventional steam turbine. Short term storage made of alumina “saddles” will be used to provide a useful thermal storage capacity of 33 MWh, equivalent to about 1 h of operation. The heliostats are large each with an area of 91 m², and total heliostat area is 89 271 m². They are relatively low cost heliostats at US\$108 per m² installed. Land area occupied is not stated but appears to be about 500 000 m². The annual net electric efficiency based on tracked solar beam will be 12% gross (10.5% net) but future scaling up to 30 MW(e) would yield more than 20% gross.

3.3. Distributed tower systems

While there is continued interest in using dish concentrators for distributed systems, these have tended to be more suited to isolated environments. Dish systems are not ideal in urban environments because of poor land usage and appearance. Emphasis in urban use of two-axis systems seems to be shifting to distributed tower technology.

Romero et al. (1999) have pointed out that the centralised tower concepts are at odds with the increasing trend to distributed generation in fossil fuelled plant under deregulated generation and transmission. They propose that modular integrated utility systems (MIUS) be assessed as a means of meeting renewable energy. The Romero paper includes the calculated engineering example of a tower using a 1.36 MW(e) Brayton turbine based up a 26 m tower and a heliostat area of 6624 m² in a land area of 38 000 m², but the authors claim that an altered optimisation would halve this high land occupation. The Schelde Heron turbine has a peak efficiency using solar energy of 39.5% compared to 25–34% for smaller turbines. Such turbines also have a significant waste output which can be used for process heat near the point of the solar plant site, allowing combined heat and power applications and high use of solar beam.

In Australia, our multi-tower solar array (MTSA) (Schramek and Mills, 2000a,b) goes one step further toward an urban tower technology. The MTSA (Fig. 9) is based on a unique, optical concentration technology which allows extremely closely spaced reflectors (>90% of ground area) and high delivered output from an area of roof or ground. In excess of 90% of annual solar beam radiation striking an area of ground or roof can be captured using extremely closely spaced reflectors recently developed (Schramek and Mills, 2001).

The basic MTSA components are:

- A reflector field using extremely closely spaced silvered glass reflectors of a special shape to allow extremely close spacing.
- Multiple receivers of radiation using advanced thermal and photovoltaic absorber technology.
- Means allowing the receivers to be placed above the reflector field between 8 and 12 m high. These may

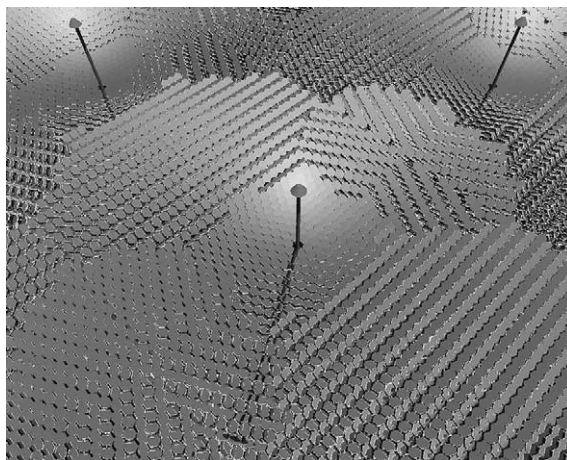


Fig. 9. A visualisation from the air of a multi-tower solar array (MTSA).

be multiple small towers or posts, or else arch-like structures.

For the receiver of radiation, MTSA can simultaneously use high-temperature and photovoltaic absorbers in parallel by splitting the incoming solar beam spectrally so that electricity production is optimised. Beam splitting has been investigated by Solar Systems in Australia and the Wiezmann Institute in Israel. It is perhaps analogous to advanced fossil-fuelled combined cycle systems, which use two different heat engines to optimise thermodynamic efficiency. In fossil fuel systems this is done serially, with a steam turbine running from the waste heat from a gas turbine. Beam splitting can be done so that only the energy which closely matched the PV requirements is sent to the PV receiver, raising silicon PV efficiency to 35–37%. The remainder is directed to a 70 kW(e) Brayton microturbine with peak efficiency around 25% including volumetric receiver losses. In the schematic Fig. 10, the heat engine is shown on the top but having it on the bottom is also possible.

Use of larger and more advanced microturbines may eventually allow 32% conversion efficiency including losses in the volumetric receiver. Peak total system efficiency of 30% should be achievable now, and over 40% in the medium term using GaAs tandem PV cells and advanced microturbines. Waste heat from the microturbines can be used for thermal purposes or air conditioning chillers. Large plants with many towers using many larger 39% efficient solarised microturbines like the Schelde Heron turbine without PV but with a single large Rankine cycle second stage turbine would allow electrical conversion efficiencies close to 50%, and would still deliver considerable thermal energy for CHP purposes.

The MTSA project has been granted funding by the Australian Research Council and it will be supported

50% by industry, including Solahart Industries and MEEC (Italy). The small single tower prototype in Australia will be approximately 150 kW(e) and future plants would be built up from modules of this size. A commercial site in Europe has been identified. Solarised Brayton turbines will be tested in facilities in the USA, Spain and Israel during the next year and possibly in Australia in 2003.

4. Low-temperature technologies

4.1. Evacuated tubes and ORC turbines

Evacuated tubes are now in wide use in Europe, Japan, and China. There are two basic types of tubes, the all-glass type based upon Sydney University work from the 1970s to the 1990s, and the flat-metal-absorber-in-glass type which has its roots in European designs. Most tube production is now in China.

These tubes are mostly used for solar hot water production, a field outside of the subject of this paper. However, increasingly, similar modules are being used in higher temperature niches. Recently developed selective coatings are now in production in China and on sale in Europe through European and Australian manufacturers (Fig. 11).

However, such evacuated tube collectors are now being adapted to efficient operation at up to 185 °C, and will be suitable for use with a new generation of organic Rankine cycle (ORC) turbines. In these, a micro turbine generator is driven by a closed loop of working fluid. The working fluid is heated to produce vapour, which drives a micro turbogenerator, and then condenses back to a liquid whence the cycle recommences. The overall efficiency of the turbine system is 10–13%. For an evacuated tube system delivering 11 MJ/m² of thermal

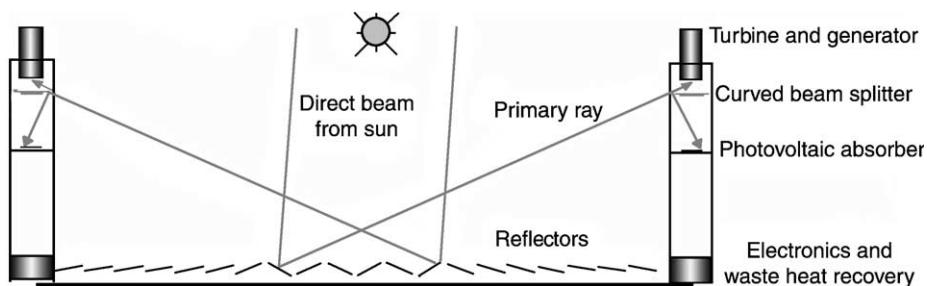


Fig. 10. Schematic of two towers of an MTSA and the reflectors between them. The reflectors far from the tower are set in alternating positions to use different tower receivers as targets, and by this arrangement minimise blocking and allow close packing. The tower support structure has not yet been designed and can take many forms, so the drawing is only indicative in a general way. The structure would be designed for attractiveness and minimum blocking of the solar beam. The curved beam splitter will be made of specially coated quartz. It will direct the green to red portion of the visible and very near infrared to the photovoltaic receiver because these wavelengths are most efficiently used by the PV, and the remainder of the wavelengths to the thermal receiver and turbine, which responds only to the energy in the beam and not the wavelength.



Fig. 11. Shows an evacuated tube collector recently developed by the Australian firm Solahart Industries. It uses tubes designed by the University of Sydney and produced under licence in China by Turbosun Ltd. The collector was designed by Solahart International with the assistance of G.L. Morrison and the author. The system is pumped with a header along the bottom.

energy per day in Sydney at 165 °C, this would amount to 1.1–1.4 MJ per day of electricity, or about 7% efficiency. This is about 55% of current PV module efficiencies but the overall system cost of delivered 24 h power might eventually be lower in the future. Free-power (2001) claim an installed cost of US\$4 ppW using a trough systems and an electricity cost of US\$0.11 per kWh(e) in Arizona and US\$0.14 in Germany but the calculation is not presented in detail.

A major difficulty at present is that the cost of the ORC engine/generators are still relatively high at about US\$2.50 ppW, almost the cost of PV panels, and evacuated tube collector panels are about US\$4.5. However, cost of the engine can be spread over many hours if storage is used, the cost of engine/generators and evacuated tubes is expected to drop in larger production. Further, simple and cheaper seasonally adjusted evacuated tube collectors designed for higher temperatures may allow much improved engine efficiency and consequent lower panel ppW costs; using pentane heat transfer fluid operating above 200 °C, the array efficiency comparable to present day PV. Either pressurised water or inexpensive thermal oil can be used as a heat transfer fluid and storage medium, a much cheaper option than the batteries used for PV. In the future, ionic fluids may be preferred (see Section 4.3.1).

For the time being, any cost advantage gained by fixed evacuated tube ORC systems over PV is likely to depend upon the need for storage and the ability to use a hot water output from engine waste heat. This seems to suggest that the first market for such ORC systems should be in remote areas such as farms and small communities where storage, CHP operation, backup by LPG, diesel or wood, and 24 h access to power would be greatly valued.

4.2. Solar chimney

Solar chimney technology is being proposed for Australia based upon German technology. Air is heated underneath a large glass structure of about 5 km in diameter, and passes up a large chimney through a wind turbine near the base as it rises. The chimney for a 200 MW(e) tower would be the tallest structure in the world, 1 km high. A company, Enviromission Ltd. has been listed in Australia to commercialise the concept but costs are not given on their web site (Enviromission, 2001). A site near Mildura is being investigated. Plants have also been proposed for South Africa and India. A Web site (Energen International, 1999) set up for a Rajasthan plant suggests a capital cost of US\$700 million, or US\$3500 per kW(e).

The first chimney was tested at Manzanares, Spain, between 1982 and 1988 and is now being proposed for sites in South Africa and India. The Manzanares plant achieved a solar to electricity efficiency of 0.53% but SBP believe that this could be increased to 1.3% in a large 100 MW(e) unit with detail improvements (Schlachich, 1995). The efficiency of these plants increases with size. The capacity factor measured at Manzanares was 10% but it is claimed this would rise to 29% in a 200 MW(e) unit. The Manzanares plant was retrofitted for a test with black plastic containing water as thermal storage and this allowed output to continue for up to 22 h. The developers claim that black mining scrap can be used for this purpose.

The SBP technology originally used plastic sheet glazing at Manzanares, but this encountered severe structural instability close to the tower due to induced vortices. Toughened glass is likely to be used for all future plants. Because of size, array-cleaning cost is an important area of concern. However, other maintenance costs associated with this approach seem to be very low.

4.3. Technical trends

4.3.1. Storage

Storage has not been encouraged by recent legislation in most countries because feed-in laws and legislative obligation programs do not have time of day rates incorporated in them. However, the imminent Spanish support system does prescribe 100% solar fraction, something that gives such storage value.

Oil storage can lead to dangerous fires like the recent SEGS trough fire in California and oil can be expensive, particularly if silicone oils are used. The major storage trend has been to molten salt, which was proved in Solar Two, will be used in Solar Tres, and is now also being considered for trough plants (Pacheco, 2001). This is mainly suitable for Rankine cycle generation. An interesting new option in the laboratory is that of ionic liquids, which are salts which are liquid at low temperature

but can be used as a heat transfer fluid up to 400 °C. These could conceivably replace molten salt in the future and allow trough systems an excellent non-flammable option for storage and heat transfer with Rankine cycle conversion.

However, storage in solid materials such as Alumina, concrete, or rock may become increasingly popular with air heat transfer systems using volumetric receivers, and may be considered in the future for use with Brayton or Stirling cycle turbines in large dish and MTSA arrays.

4.3.2. Electrical conversion

Rankine cycle engines appear to be the best option with trough plants because of temperature limitations in the latter, but Brayton cycle microturbines appear to be moving quickly to displace Stirling engines in the two axis tracking market because of much lower cost.

Low-temperature ORC engines running from evacuated tube arrays or trough systems may be feasible as PV replacement options in the future. At present these appear to be as or more expensive than PV systems because of high engine cost, except in systems with significant storage. As engine costs drop with increased production, this could change.

Israeli, Italian and Australian groups are developing beam splitter technology to produce hybrid PV/thermal systems with very high overall efficiency. System electrical efficiencies between 30% and 40% appear quite feasible.

4.3.3. Reflector

Most advanced systems now are using mechanically flexed thin (<1 mm) thick glass backed with silver. Aluminium is used now in the evacuated tube market and may in the future be used in some low cost trough systems.

4.3.4. Configuration

There appears to be a growing trend toward Fresnel systems (tower systems) in both single axis and two axis markets. These allow lower structural costs, fixed receivers and relative ease of reflector cleaning.

4.3.5. Distributed markets

There is a growing feeling that smaller modular systems may be offered easier entry into the marketplace. These can be used as combined heat and power systems where the plant is located near the point of use. Use near a city may mean a less favourable climate, but this can be compensated by the possibility of using waste heat as well as the electricity, and by offsetting retail electricity cost instead of fossil plant generating cost. Highly compact Fresnel systems such as the MTSA and CLFR may offer space and aesthetic advantages over troughs and dishes in these markets.

5. Incentives

Incentives for solar systems are available around the world in many forms, but five main categories have emerged.

5.1. Feed-in

Feed-in laws are becoming popular in Europe, with Germany being a pioneer in this type of scheme. The German plan allows anyone meeting technical standards for grid supply to obtain a guaranteed price for renewable energy fed into the grid over a 20-year period from project installation. The German laws are technology based and give, for example, higher rates to PV than to wind. The price drops gradually as targets in installed capacity are met. The high price is paid by electricity retailers. This is an excellent scheme for introducing new technology, but is very expensive for the amounts of capacity in the targets. In equity terms, the emphasis has been skewed toward small PV systems and away from larger STE systems because of project capacity limits which appear to have no environmental basis. It appears that hybrid systems are not supported by this scheme even if the fossil component is less polluting than the grid supply. Similar scheme are beginning to be introduced in France and Spain. The Spanish system will offer Euro 0.23 per kWh to direct solar systems with below 50% fossil fraction, and in this respect is more flexible than the German system.

5.2. Legislative obligation/portfolio standard

This type of measure has been adopted by 12 US states, and Australia. It is based upon total renewable energy supply supplied as a fraction of total generation by a given target date. The electricity distributors and generators bear the obligation in the USA, and only the distributors in Australia. These groups pay the excess cost in the Australian system, and are allowed to seek the lowest cost technology option; the government pays nothing. The low cost choice ensures strong competition between established renewable energy technologies such as wind, biomass and direct solar. In Australia, solar domestic hot water systems are also included in the plan as an electricity offset. Interestingly, in Australia the expected dominance of biomass has not occurred, with wind and SDHW expected to take the lion's share of the 2010 market, which is pegged at 2% of generation for new renewables by 2001 (added to about 10% of hydro already existing). In the USA states total RE targets vary widely. In no case are the targets related to atmospheric requirements for stability in 2050, but the process can be upgraded over time. Importantly, in the Australian programme penalties for opting out of the system are far too low.

5.3. Price support

This is used in many countries, particularly with PV systems. These are technology specific and contain equity difficulties with regard to which technologies are supported and which not. This is a primary support mechanism for PV in many countries without specific portfolio support or high feed in law prices. A support price of A\$5 per peak watt is used in Australia because PV cannot compete in legislative obligation or REC programmes. This is not available to solar thermal electricity, creating an equity imbalance. Direct subsidies are notorious for lack of long term success, because when they are withdrawn, the industry collapses.

5.4. Tradable certificates

This is being pioneered in Australia in the form of renewable energy certificates (RECs) which are based upon a government assessment of the greenhouse abatement effectiveness of the particular technology. These are assigned to the purchaser of the technology and may be sold to other companies who require them to meet government REC requirements for that industry. These are suitable as a long term measure to assist legislative obligation programmes and the requirements of those obligated to collect RECs would be expected to rise with time to continue market growth. In Australia, these have been highly successful in stimulating the solar hot water and wind generation markets. They avoid equity difficulties because they are performance based. The RECs received by the customer are determined on the basis of electricity avoidance, but there is as yet no REC value accorded to thermal energy produced in CHP systems.

5.5. Green power

These schemes allow individual consumers to pay more for their electricity to ensure that the money is directed to the construction of new renewable energy plant or the purchase of renewable energy from IPPs. They are popular now but limited in total market share because most consumers are unwilling to bear the significantly higher cost while fellow consumers continue to pay low fossil fuel costs. These schemes appear to be reaching saturation because of the entrance of other types of government incentives which are shared by the whole of society.

5.6. Discussion of market incentives

In the view of the author, no country has a perfect scheme but examination of the current approaches suggests the direction in which nations should move. The author proposes that a combination of measures

can be supplied in a form in which there is little outlay by government and high attention is paid to equity of treatment and competition between technologies. This would include:

1. A renewable R&D fund financed by a levy on fossil fuel sales by primary energy companies.
2. A market buildup scheme based upon legislative obligation/portfolio standard, assisted by tradable RECs as in the Australian model based upon delivered kWh to the grid. Unlike the Australian programme, this should include high penalties for non-compliance. Such a program can be linked to national or state goals. The targets should be challenging but achievable, and should be based upon consistency with global environmental stabilisation of the atmosphere. Hybrid renewable fossil installations should include a fossil technology component which is significantly less emitting than existing total grid generation emission rate per kWh produced and, obviously, the fossil component should not be counted as renewable generation. The Spanish allow up to 50% fossil fuel in their upcoming programme for solar thermal electricity.
3. A prototype commercialisation/cost reduction scheme to introduce indigenously developed or preferred new foreign technology. This could be based upon a feed-in law with caps at a certain target of MWh delivered, but the author believes that this could be better achieved by a high "premium REC" rate which would decline in a specific rate until the pre-determined target of MWh delivered has been achieved, at which time the normal REC rate applies. This would remove present equity problems between technologies and allow tradability.
4. Abandonment of special subsidies for particular technologies as inequitable and market inefficient. The author is not in favour of removing current high subsidies for PV unless measure 3 is implemented at a logically high level of REC premium value and MWh target level so that PV can reduce costs by high production rates; however, solar thermal electricity and other new renewable energy technologies should have access to similar premium value levels and MWh targets. This will ensure equity of treatment between these technologies. If solar thermal electricity and other clean technologies proceed more quickly than PV in such an environment, that should be accepted as a simple expression of relative environmental cost-effectiveness in a fair market.
5. Inclusion of thermal and clean chemical outputs in REC value assessment. This would allow the full environmental benefit of solar CHP and solar fuel technologies to be included in the programme seamlessly. Importantly, this would also allow SDHW and solar process heat technologies to become attractive

options for distribution utility life cycle financing, ensuring that these are not disadvantaged relative to central systems.

6. Markets

6.1. Next 5 years

Over the next 5 years there will be a great increase in solar thermal electricity commercial activity in developed countries through feed-in and/or REC programmes, beginning with feed-in laws in Spain. Green power will probably be replaced by such initiatives. The Global Environmental facility is also available to assist projects in developing countries, but bureaucratic problems continue, and adequate measures in developed nations would cause the developed nations to be the largest market. Equity and completeness in the incentives for renewable energy technologies will cause a sudden surge in solar thermal electricity activity. As with wind today, storage is not a prerequisite at this stage because the renewable energy contribution will continue to be small. However, it will be required in some specific situations for local reasons such as inadequate grid supply, and in communities which are not grid connected.

6.2. Next 50 years

Over the next 50 years, the market for direct solar electricity must increase enormously so that climate goals can be reached. Direct solar generation has the least restrictions in resource base and is required to meet expected generation requirements, even under very high energy efficiency assumptions. In Mills and Dey (2001) we have suggested that direct solar growth rates must exceed 25% per annum for the next 30 years in order for direct solar generation to achieve a dominant market position by 2050. The net contribution of direct solar will be small before this time. To access the market after 2030, significant storage will have to be installed with such systems for grid stability.

7. Summary

This is an exciting time for solar thermal system development. Many new technologies and materials are emerging into the marketplace have been described and some developed countries such as Spain are offering strong incentives for new projects. There is little doubt that new distributed technology options and retrofit to existing fossil fuel plants will allow new avenues for transitional market growth.

However, current market incentives do not offer solar thermal electricity an equitable share of the market because initial commercial prototype development is not supported in most countries with adequate support mechanisms for demonstration and production related cost reduction. Creation of improved mechanisms must move in the direction of equity between technologies, measure to encourage introduction of large systems employing new technology, improved market competition, legislative obligation assisted by tradable certificates based upon environmental performance, and inclusion of thermally based environmental benefits to assist solar CHP systems and end use pure solar thermal systems.

A proposal has been put forward in this paper for a collection of measures which has little cost to governments and is based upon environmental performance. In such an environment, solar thermal electricity will thrive and society will obtain the best environmental result for the money spent.

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