THE DEVELOPMENT AND TESTING OF SMALL CONCENTRATING PV SYSTEMS

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Abstract - Spreadsheets have been used to compare some 90 possible small PV concentrator designs that might be suitable for use at remote sites. They have apertures of about 2m^2, use BP Solar LBG cells, and employ small aperture modules to reduce heat sinking and construction costs. Designs include fixed V-troughs and CPC's, single axis tracked cylindrical lens and mirror systems, and 2-axis tracked spherical-symmetry systems. Performance and volume production costs were estimated. Four promising systems were constructed as prototypes:

- **A** - Point-focus Fresnel lenses, 2-axis tracking; Cg = 32x; and 69x with secondaries.
- **B** - Line-focus mirror parabolic troughs, 1-axis tracking, Cg = 20x.
- **C** - SMTS ('Single-mirror two-stage'), 1-axis tracking, Cg = 30x.
- **F** - Multiple line-focus mirror parabolic troughs, E-W 1/day manual tracking, Cg = 6x.

The prototypes were tested at Reading, and three for up to a year's field trial at ZSW's test site, Widderstall, in Germany. The best system efficiencies, normalised to 25°C and excluding the end losses of linear systems, were 12.5%, 13.2%, 13.6% and 14.3% for collectors **A**, **B**, **C**, and **F**, respectively. The collectors were practical and robust, and the performances of collectors **B**, **C** and **F** are only 10% below the estimates in the spreadsheet calculations. The best collectors have estimated production costs between 1.5 and 1.8 US $/Wp, yielding energy costs at a good site (excluding BOS and overheads) of between 5 and 7 cents/kWh (18 and 25 cents/MJ). On the same cost basis a conventional PV array costs 4.3 $/Wp, and 18 cents/kWh (65 cents/MJ).

1. INTRODUCTION

Photovoltaic systems have advantages as sources of small amounts of electrical power in remote areas, but conventional solar panels are expensive. Since lenses and mirrors in volume cost only about 1/20 as much as solar cells, it should be possible to reduce the cost of PV electricity by using them to concentrate the sunlight from a large area onto a small area of solar cells.

Many concentrators have been developed in the past, but they have usually been not much cheaper than conventional solar panels, because concentrator solar cells have cost much more than one-sun cells and the optical and tracking systems have been expensive. Recent developments, such as BP Solar's (Now BP Solarex's) Laser Buried Grid cells (Mason, Bruton and Heasman, 1995), have made it possible to manufacture solar cells little different in design and cost from one-sun cells that can be used at concentration ratios up to 40x. Using these cells with optical and tracking systems that are no better than required there is considerable scope for cost reduction.

This JOULE III project built on the progress made in a previous JOULE II project, EUCLIDES (Sala et al., 1997), led by BP Solar and joint with UPM, ZSW and Reading University, which developed a PV concentrator for large grid-connected systems. A 480 kWp demonstration plant, based on the EUCLIDES work, has been built in Tenerife (Sala et al., 1998).

In the present project the objective instead has been to reduce the cost of PV electricity by developing small concentrating systems of about 2 m^2 aperture designed for use in remote areas. Specifically, the aim has been to produce a small number of prototypes of such systems sufficiently near practical production to be of interest to industrial companies. We have examined a wide range of possible concentrators using BP Solar LBG cells. For each system, performance and cost have been estimated on common basis, assuming large-scale production. No such comparison of a wide range of PV concentrator systems been made for many years.

2. THE COMPARATIVE ANALYSIS OF A WIDE RANGE OF POSSIBLE CONCENTRATING SYSTEMS

Irradiance data were assembled for three representative sites: Almeria, Spain, a particularly good site with a mean annual global irradiance on a horizontal surface of 1734 kWh/m^2 , Manfredonia, Italy, with 1580 kWh/m^2 , and Widderstall, Germany, a rather cloudy site with only 1058 kWh/m^2 . A database of materials costs was generated from manufacturer's quotations. Using these data, some 90 possible small PV concentrator designs suitable for use at remote sites were compared (Whitfield et al., 1997, 1998). The systems envisaged have apertures of 2 m^2, use BP Solar LBG (laser buried grid) cells, and are composed of smaller aperture modules to reduce heat sinking and construction difficulties. Designs considered included:

- fixed V-trough and CPC (compound parabolic collector) systems,
- cylindrical single-axis tracked systems up to 30x,
- spherical-symmetry 2-axis tracked systems up to 69x,
- secondary optics, and a variety of manual and automatic tracking strategies.

The performance of each system was calculated on a spreadsheet, taking due account of its dimensions, the properties of the optical components used, the efficiency of the solar cells, and the energy capture of the tracking strategy chosen. Each system was then given outline mechanical design, bearing in mind ease of mass production and long service life. Using this mechanical design, each system's material cost was calculated, and with advice from a consulting engineer, the manufacturing cost in mass production (1.5 MW, or 10,000 collectors per year) was estimated. The total cost was combined with the estimated performance to give the resulting cost per peak watt, and per kWh.

Typical results are given in Table 1, which shows the cost per peak watt and per kWh for the best of the collectors considered and a few others. The main conclusions from the analysis are:-

1. Concentrating collectors can be much cheaper than conventional planar collectors, by a factor between 2 and 3.
2. To obtain this improvement, they must be made in large numbers.
3. There is a wide range of good designs. The best have relatively high concentration ratios and imaging primary optical systems.
4. Mirrors are usually more cost-effective than lenses.
5. Secondary optical elements often improve the performance.
6. Automatic tracking systems are better than manual tracking, in spite of their extra cost.

3. SELECTION OF COLLECTORS FOR PROTOTYPES

From the information in section 2, the project group then unanimously (!) selected six collectors, **A** to **F** in Table 1, for more detailed analysis; of these six collectors, four, **A**,**B**,**C** and **F**, were built as prototypes. Selection criteria included not only low cost, but also innovative optics (SMTS, single-mirror two-stage) (Alarte, Benitez and Miñano, 1998), and innovative tracking (once per day movement). Calculations were then made to optimise the parameters of each collector, particularly the concentration ratio and aperture, to maximise the performance/cost ratio.

In the detailed design, attention was paid to ease of large scale manufacture; for example cylindrical parabolic mirrors could be pressed from aluminium sheet or moulded in plastic, and lenses could be made by a rolling process. But the press tools and moulds were too expensive for these techniques to be used for our prototypes. So the prototypes were built with supporting ribs or fibre-glass members to maintain the optical shapes. Care was also taken to use techniques and materials that would ensure a long working life and freedom from corrosion.

3.1 The choice of mirror surface

For the reflector surface of the three mirror collectors (**B**, **C** and **F**) we essentially had the choice between four materials; where the costs shown are our assumed very large order prices (Areas of 20,000 m^2, corresponding to production of 10,000 collectors/year).

3M's ECP305+ silver film, exterior grade;	reflectivity 0.94;	cost \$ 25/m^2
3M's SA-85P aluminium film, exterior grade;	reflectivity 0.85;	cost \$ 7/m^2
3M's SS-95P silver film, interior grade;	reflectivity 0.94;	cost \$ 9/m^2
Anocoil anodised aluminium;	reflectivity 0.84;	cost \$ 20/m^2

Note: The first three mirrors are reflective film, so the cost of substrate and laying down must be added, typically \$ 12/m^2.

A comparison of ECP305+, SA-85P and SS-95P was carried out, using the cost/performance spreadsheets for collector **B**; for this comparison, the reflectivities were reduced to 0.90, 0.81 and 0.88 respectively, to allow for mirror profile errors. The annual energy cost, in c/kWh, was highest for ECP305+, marginally less for SS-85P, and about 7% less for SS-95P. Anocoil anodised aluminium was not include in this analysis, as it was more expensive than SA-85P, which has a higher performance. In collectors **B** and **F** the parabolic troughs are covered with glass or acrylic sheet, so the reflective surface need not be especially weather-resistant, and we used the SS-95P interior grade film. For collector **C**, where the reflector is in the open air ECP305+ was used.

3.2 Heat sinking

Heat sinks for the cell strings were designed to hold the cells at temperatures similar to those of conventional flat arrays, typically 30-40°C above ambient. This requires an effective cooling area approximately twice the projected area of the array; for a flat array this is just the front and rear surfaces; for collectors **A**, **B** and **F**, there were suitable aluminium surfaces forming the structure or mirror surface of the collector. Studies carried out in the previous (EUCLIDES) project (Whitfield et al., 1997) and thermal tests on small mock-up collectors showed that adequate cooling would be obtained with the 0.5 mm aluminium sheet if the aperture was not above about 15 cm. So this aperture was chosen for collectors **B** and **F**.

3.3 Trackers

Time did not permit the development of custom-built trackers for each collector, although they will be necessary to reduce the cost of production systems. So commercial systems were purchased from the USA. Collector **A** uses a 2-axis active tracking system from Wattsun, with a sensing head on the inner gimbal driving right ascension and declination servos. Collectors **B** and **C** use an open loop microprocessor-controlled system, developed initially by Maish of Sandia (Maish, 1991), and marketed by Enhancement Electronics; this drives a Wattsun servo, rotating the collector about a polar axis. The systems were reliable and weatherproof, but were stronger, heavier and more expensive than was required for small systems. The microprocessor-controlled systems were difficult to set up, but ran well once this had been done.

3.4 Solar cells

The solar cells used for the project were BP Solar ‘Saturn’ laser buried grid cells (Mason, Bruton and Heasman, 1995). These cells, developed from work by Prof. Green of the University of New South Wales, Australia, can be made for little more than the cost of conventional screen-printed one-sun cells, but have inherently higher efficiency and lower series resistance; this makes them particularly suitable for moderate concentration ratio concentrators such as ours. In the spreadsheet analyses we assumed that unmounted planar arrays cost 4 \$/Wp, or about 690 \$/m^2. The concentrators use much smaller cells than planar arrays, and BP Solar advised that mounting costs would be very high; so we increased the cost by a factor (1.3 + Concentration Ratio/20) , giving a range from 1050 to 2660 \$/m^2 for encapsulated cells for the collectors considered.

The cells were cut to a length of 50 mm and widths appropriate for each collector, retaining a full length bus bar down one side. They were connected in strings with conventional tabbing strips, using thicker than usual material to keep the resistance down. The strings were mounted on machined aluminium carriers, using a thermally-conducting electrically-insulating tape, and encapsulated in transparent silicone, with glass or Tefzel covers. This technique was satisfactory, but was rather slow and messy.

3.5 End losses of cylindrical collectors.

Collectors with cylindrical optics, such as linear Fresnel lenses or cylindrical parabolic mirrors, concentrate the light into a line focus; the solar cell string is mounted along this line, and the collector is rotated about an axis parallel to this line to keep the focal line on the cell string. If, as is common, the chosen axis points at the pole, then tracking is perfect at the equinox; the sun’s rays are perpendicular to the axis of the collector, and the cell string can be as long as the mirror. But at any other date the focal line is displaced towards or away from the pole. At the solstice, when the declination δ reaches its maximum value of 23.5^o (Figure 1), a length $2h \tan\delta$ of the cell string is not illuminated. At the other solstice, an equal length is shaded at the other end of the cell string. Since one shaded cell blocks the whole output current of the string, it is usual to reduce the cell string length to $d - 4h \tan\delta$, so that the whole of the cell string is always illuminated. The output of the collector is reduced proportionately. This end loss has been computed for each collector and included in the spreadsheet analyses. With long narrow collectors the loss is small, but with wider apertures it becomes significant. For collector **B**, a narrow offset paraboloid, the correction for end losses is a factor of 0.89, but for collector **C**, the wide SMTS collector, it is 0.65.

This end loss can be eliminated by using a gimbal mounting and two-axis tracking, but this adds cost and mechanical complication. But a partial solution is to use a full length cell string and bypass diodes (Figure 2). Suppose that there are n cells in the centre part of the string that is never shaded, and m cells at each end that are shaded at the solstice. Then a full string is n + 2m cells, and the correction for end losses if the shaded cells are omitted is n/(n+2m).

If the shaded cells are fitted in the collector, then at the equinox, all the cells are illuminated and there is no end loss. In the worst case, at a solstice, m cells at one end only are shaded, and the output is that from n + m cells. One bypass diode will be turned on, and the voltage drop across it will be about the same as the output voltage of one cell. So the output at a solstice will be that from n + m - 1 cells. Away from the solstice, fewer than m cells will be shaded and the output will increase. So the mean end loss will be less than half that when the shaded cells are omitted; for collector **C** the correction factor is increased from 0.65 to about 0.83. (A full calculation of the loss factor depends on the distribution of sunlight through the year, and has not been attempted). The cost of the extra 2m solar cells is small, and the cost of the diodes is negligible. The cost per peak watt of collector **C** is reduced from 2.39 \$/Wp to about 2.06 \$/Wp.

Of course the voltage of the peak power point changes as cells are shaded, and so a true peak power tracker and appropriate array to load converter are needed in the system; but they should be provided anyway for an optimal design.

4. DISCUSSION OF SPECIFIC COLLECTORS

4.1 Collectors built as prototypes

4.1.1. Collector **A**, Point focus Fresnel lens, with two axis tracking

This collector (Hunt, 1998) is a two-axis tracked, point focus system using flat acrylic Fresnel lenses (Figures 3, 4). As such, it is similar to many previous systems, including the original Martin Marietta Soleras collectors (Salim and Eugenio, 1990), various Sandia designs (Chiang and Quintana, 1990), and collectors from Alpha Solarco (Carroll, Schmidt and Bailor, 1990) and Midway. The advantages of this design include:-

- maximum beam insolation collection due to two-axis tracking
- potential for simple mass-produced optics,
- the use of the housing as heat sink;

while the main disadvantages include:-

- the increased cost of the second axis tracking,
- the fact that flat Fresnel lenses are less efficient than domed ones at f-numbers below about 1.1, because the reflection losses at the second surface are high due to the large angle of incidence.

The collector of this project differs from previous similar systems primarily in the use of only moderate concentration levels, and hence the ability to use the commercially-priced essentially one-sun technology LBG cells. It has the potential to incorporate a secondary optical element, to raise the concentration ratio, or to increase tolerance to tracking errors. Half the collector, **A1**, was fitted with small plane mirror secondary concentrators, and the other half, **A2**, was not.

This collector is an easy device to manufacture in volume. The acrylic lenses are made by 3M’s calendaring process, already used in volume for street signs, while the aluminium sheet housings can be pressed to shape. The cells are relatively large, so either manual or automated tabbing, encapsulation and mounting are straightforward.

4.1.2 Collector **B**, Multiple offset cylindrical paraboloid, one axis tracking

This collector (Weatherby and Bentley, 1998) was designed for polar axis tracking (Figures 5, 6). The concentration ratio was 20x. A single module consisted of two cylindrical parabolic mirrors, each with an aperture of 150mm x 1.5m, formed from thin (0.5mm) sheet aluminium alloy laminated with SS-95P reflective material. The mirrors were arranged back to back so that the two 7.5mm wide strings of cells, located near to the focal lines, were on the outer walls of the module, to facilitate the cooling of the cells. The cooling was further enhanced with a fin extending towards the sun. A simple glass or acrylic cover was used to protect the optics and add strength to the module. Advantages of this collector are the simple modular construction and the ability to mass-produce the housings by an inexpensive stamping method. The cooling arrangement removes the need for bulky expensive heat sinks whilst keeping the cells at temperatures no higher than those of conventional flat panels.

To avoid the cost of the large press tools necessary for mass production, a series of fibre-glass ribs were moulded and used to retain the mirrors in their parabolic form. One disadvantage of this technique is that the ribs obstruct the convective flow of cooling air. It is expected that mass-produced modules, with no ribs, will give better cooling and even better performance than the prototype.

4.1.3 Collector **C**, Single-mirror two-stage (SMTS) collector, single axis tracking

The SMTS collector (Figures 7, 8), (Alarte, Benitez and Miñano, 1998) presents some characteristics that make it a good candidate for achieving the required cost reduction. In particular:

a) Since the cell strings and the heat sinks are at the mirror edges, the heat sinks can form part of the mechanical structure of the collector, reducing the mass and cost of other structural material.

b) There is only one mirror per pair of concentrators, in such an arrangement that two concentrators share their mirror so that each half of the mirror works as a first stage for one concentrator and as a second stage for the other. The collector has a high acceptance angle of ± 1.5°, around 90% of the theoretical maximum corresponding to its concentration, while maintaining the structural simplicity of a parabolic trough collector, whose acceptance angle reaches no more than 50% of the theoretical maximum. This high concentration-acceptance angle product makes the collector less sensitive to tracking or manufacturing errors, which again reduces the manufacturing cost.

The prototype mirrors were made in sections 25 cm long, of fibre-glass, on a numerically machined former. They were silvered with ECP305 film, and bolted to the heat sinks. The spreadsheet analysis showed that it would be most cost-effective to use a two-axis tracking system; however for mechanical convenience a single-axis polar mounting was chosen for the prototype. The loss, due mainly to end losses, can be allowed for in subsequent analysis. Collector **A** (Section 4.1.1 above), provided experience with a two-axis tracker.

4.1.4 Collector **F**, Multiple offset cylindrical paraboloid, moved manually once per day

Of the four prototype collectors, this one (Figures 9, 10), (Weatherby and Bentley, 1998) is designed to be the simplest and most robust, as no automatic tracker is required. It consists of parabolic troughs that run E-W, so that as the sun moves approximately along the axial plane of the parabola the focal line moves mainly E-W along the line of cells. The collector tilt is designed to be manually re-aligned every day, or every few days, to accommodate the changing declination of the sun. Even so, except at the equinox, the sun moves along a small circle, and so moves a little in a N-S direction off the great circle defined by the axial plane of the parabola. The width of the cells has to be greater than the width of the focal line, to allow for this N-S movement. The chosen geometrical concentration ratio is 6x, giving an acceptance angle of about 7°, which allows the sunlight to fall on the cell string for about 8 hours on most days. The E-W movement of the sun gives a cos θ loss, a factor of 0.5 at 4 hours from noon, and also significant end losses; these have been minimised by using long mirrors, and by the by-pass diode circuit of section 3.5.

The design of the collector envisages a very simple process for mass-production:

- the full $2m^2$ reflective sheet is stamped to profile,
- the cell strings are attached,
- the glass cover is bonded in place.

For the prototype, we could not afford the tool for a stamping, and a rather elaborate fabrication of the parabolas, supported by a lattice of aluminium ribs and cross-members, was used instead.

4.2. Collectors assessed but not built

4.2.1 Collector **D**, Cylindrical paraboloid, with secondary concentrators and single axis tracking

This was another promising design, slightly more costly than **A**, **B** and **C**, but cheaper than **F** and **G**. It was not selected for manufacture in this project because we had already chosen two better mirror systems, and we wanted to include a system with manual movement instead of automatic tracking.

4.2.2 Collector **E**, Linear Fresnel lens, with solid CPC secondaries and two axis tracking

This collector, although more costly than some of the others, has the advantage of being simple and totally enclosed. Some work was done on the manufacture of prototype linear lenses, by machining them from acrylic sheet, but it was not possible to polish the milled surfaces to a sufficiently good finish in a reasonable time. Some lenses are commercially available, but they are designed for other purposes and are not of the correct dimensions for our collector. Special lenses could be made to our design by 3M, but the cost of a prototype was prohibitive. So this design was abandoned.

4.2.3 Collector **G**, V-trough, with single axis tracking

This collector is not so cheap as the best collectors, but it is much nearer to practical production, as the solar cell a rrays can be conventional planar arrays, the optical design and construction of the mirrors is not critical, and a cheap thermo/hydraulic tracker can be used. But the prototype, being built by ZSW under another programme, was not ready in time for this project.

5. TESTING

All the prototype collectors (Table 2) were built at Reading. During construction, the solar cells were all individually tested on a computer controlled laboratory tester, to reject faulty ones (in fact, none) and to select matched sets for each string. The variation between cells was small, and perhaps due to measuring errors; it was probably unnecessary to select at all. The peak efficiency of the cells used was about 18 %, corrected to 25°C, at an irradiance of 15 kW/m^2, falling to about 17 % at 4 and 37 kW/m^2.

The cell strings were tested at 1-sun, to check for faulty connections, before being fitted to the collectors. As soon as they were completed, the collectors were tested for a short period, measuring spot performance and I-V curves. The results are summarised in Table 3, 'Measured Efficiency', 'Best Module' and 'Collector'.

Three of the collectors, **A**, **B**, and **F** were then sent to ZSW's test site at Widderstall for long term testing. A computer-based data logger was used to record, at one minute intervals, output current, voltage and power at the peak power point, cell temperature, tracking accuracy, and a range of meteorological data, notably direct and global insolation, ambient temperature, and wind strength and direction. From time to time I-V curves were taken. Collector **A1**, the point-focus Fresnel lenses with secondaries, had too high a concentration ratio; its efficiency was low, and local heating of the cell encapsulation was causing damage, so it was taken out of service. Collector **A2**, without secondaries, was used throughout the trials.

Typical results for irradiance and output power for a clear warm summer day (8th August 1998), are shown in Figure 11. Direct beam irradiance was above 800 W/m² for more than 8 hours. The daily total of the direct normal irradiation was 10180 Wh/m² (36.7 MJ/m^2), and of the total normal: 11393 Wh/m² (41.0 MJ/m^2); only about 10% of the available solar energy was diffuse. Ambient temperature was between 20°C and 29°C and wind velocity between 1 m/s and 2.5 m/s during the period that the direct radiation exceeded 800 W/m². The 2-axis tracked collector, **A2** was in operation for about 12 hours; the end switch stopped further tracking in the evening. The fixed collector **F** was active for approximately 8 hours, and the polar axis tracked collector **B** for more than 12 hours. The total generated energies for this day were 725 Wh (2.61 MJ) for Collector **F**, 505 Wh (1.82 MJ) for Collector **A2** and 1239 Wh (4.46 MJ) for Collector **B**.

Collectors **B** and **F**, tested at Widderstall, proved to be reliable practical units. They withstood a year of weather with no significant deterioration. Heat sinking proved satisfactory, with cell temperatures 30°C to 45°C above ambient, similar to conventional flat panels. The test results are summarised in Table 3. The best module efficiencies, normalised to 25°C and excluding the end losses of linear systems, were: 12.5%, 13.2%, 13.6% and 14.3% for collectors **A2**, **B**, **C**, and **F**, respectively. Full systems performed somewhat worse than their best modules, due to manufacturing variations. Incidentally there was no evidence to support the commonly held view that variations of intensity along the line of cells make cylindrical mirror concentrators impracticable for PV systems.

There were two serious problems revealed by the tests:-

1. Collector **A**, using point focus Fresnel lenses had a concentration ratio of 32x without secondaries, and 69x with secondaries, too high for the cells used, which were optimised for 15 suns, causing a loss of efficiency at the higher concentration. The cure is to use cells optimised for a higher concentration ratio, or to redesign the optical system to lower the concentration ratio.
2. Collector **C**, the single mirror two stage concentrator was made of fibreglass (GRP) mouldings, coated with a silvered plastic reflecting film. The intensity of sunlight on the secondary part of the mirror was sufficiently great to burn the GRP wherever there was a flaw in the mirror. So, although the optical performance was very good, the collector would not be reliable in use. The cure is to build the mirror from aluminium, to spread any local heating over a reasonable surface area.

6. CONCLUSIONS

Several designs of small concentrator systems can be significantly cheaper than conventional planar arrays, reducing cost/watt and cost/kWh by a factor of 2 or 3. To achieve such reduced costs, the concentrators should be designed to use minimum amounts of material, and be manufactured in such a way, and in sufficient quantity, as to keep down the manufacturing cost.

Prototypes of four designs of concentrator were built by hand. Design and construction, though taking longer than anticipated, presented few problems. Three were tested for some months at ZSW's test site at Widderstall. Overall, the prototypes have behaved roughly as we expected; they have proved to be robust and reliable, and capable of operating for long periods in the field. The performance figures from the tests generally support the estimates entered in the spreadsheet calculations. For collectors **B**, **C** and **F**, best prototype module outputs ranged from 7% to 13% below the expected performance figures. Collector **A**, where the cells were run well above their design concentration, gave a performance (without and with secondaries) of 22% and 37% below expectation. On the basis of the spreadsheet data, the best of the collectors have costs in the region of 1.5 to 1.8 US $/Wp, yielding energy costs at a good site (excluding BOS and overheads) of between 5 and 7 cents/kWh (18 and 25 cents/MJ). The corresponding figures for a fixed planar PV array are 4.3 $/Wp, and 18 cents/kWh (65 cents/MJ).

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Table 1. Results for the best collectors analysed, and a few others. The last line is a conventional planar array.

Prototype Code	Primary Optics	Secondary Optics	Mounting	Conc. Ratio	Cost $/Wp	Cost Cents/kWh		
						Wid.	Man.	Alm.
A1	Point focus Fresnel lens	Pt-focus solid CPC	Gimbals	69	1.46	12.1	6.2	5.4
A2	Point focus Fresnel lens	No	Gimbals	36	1.48	12.2	6.3	5.4
B	Offset cylindrical Paraboloid	No	Polar	19	1.62	14.0	7.2	6.2
	SMTS collector, plastic, 0.6m	Yes	2-axis	30	1.78	14.7	7.6	6.6
	Multiple offset cylindrical paraboloid	No	Polar	20	1.78	15.4	7.9	6.8
	Cylindrical paraboloid	No	2-axis	20	1.95	16.1	8.3	7.2
	Cylindrical paraboloid	Point-Focus CPC	Polar	65	1.78	16.2	8.3	7.2
	Multiple offset cylindrical paraboloid	Mirror CPC	Polar	27	1.88	16.3	8.4	7.2
D	Cylindrical paraboloid	Solid CPC	Polar	37	1.90	16.4	8.4	7.3
E	Linear Fresnel lens	Solid CPC	Gimbals	37	2.02	16.7	8.6	7.4
	Cylindrical paraboloid	No	Polar	20	1.95	16.8	8.6	7.5
	Curved TIR lens	No	Polar	28	1.97	17.0	8.7	7.6
	Cylindrical paraboloid	Mirror CPC	2-axis	25	2.06	17.0	8.8	7.6
	SMTS collector, aluminium, 0.3 m	Yes	Polar	30	2.00	17.3	8.9	7.7
	SMTS collector, aluminium, 0.3m:	Yes	Polar	30	2.01	17.3	8.9	7.7
	Cylindrical paraboloid	Oil filled CPC	Polar	37	2.04	17.6	9.1	7.8
	Cylindrical paraboloid	Point-Focus CPC	Chinese	50	1.72	19.5	9.6	8.3
	Curved Fresnel lens	No	Polar	15	2.18	18.8	9.7	8.4
C	SMTS collector, plastic, 0.6m	Yes	Polar	30	2.39	21.6	10.6	9.2
G	V-trough, screen printed single crystal cells	No	Polar	2	4.31	23.7	13.9	12.7
	Multiple offset cylindrical paraboloid	Mirror CPC	E-W axis 1/day	8	2.52	31.4	15.8	13.6
F	Multiple offset cylindrical paraboloid	No	E-W axis 1/day	6	2.64	32.8	16.6	14.2
	Flat, screen printed single Crystal cells	No	Fixed at latitude	1	4.31	30.5	19.6	18.1

Note. The costs given in the table are for cells, optical systems, mountings and trackers only, including construction costs; balance of system costs are omitted as they are similar for all types of collector. The cost in $/Wp is for collectors at operating temperature, and for concentrators is based on direct beam irradiance of 850 W/m^2; the cost for the flat plate is based on a total irradiance of 1000 W/m^2. The cost in cents/kWh is site-specific; the three columns are for Widderstall, near Stuttgart, a relatively cloudy site, Manfredonia in Italy, and Almeria in Southern Spain, a particularly good site. (For cost in cents/MJ, multiply cents/kWh by 3.6).

Table 2. The prototype collectors.

Code	Primary Optics	Second-ary Optics	Concen-tration. Ratio	Module Width (m)	Aperture (m^2)	Axes: Tracking
A1	Point-focus Fresnel lens	Yes	69x	0.225	0.81	2-axis:cont
A2	Point-focus Fresnel lens	No	32x	0.225	0.81	2-axis:cont
B	Parabolic Mirror	No	20x	0.15	1.80	Polar:cont
C	SMTS	Yes	30x	0.30	2.40	Polar:cont
F	Parabolic Mirror	No	6x	0.15	1.80	E-W:1/day

Table 3. Summary of costs and performances of the prototype collectors.

			From Spreadsheets			Measured Efficiencies (%)*			
Code	Optics	Conc. Ratio	Cost $/Wp	Cost c/kWh*	Effcy. (%)*	Best Module	Coll-ector	ZSW Spot	ZSW Long*
A1	Pt-focus Fresnel	69x	1.46	5.4	15.5	9.8	9.4	2.5 – 5.0	2.2 - 3.2
A2	Pt-focus Fresnel	32x	1.48	5.4	16.0	12.5	12.3	8.0 – 11.0	7.0 - 8.5
B	Parabolic mirror	20x	1.62	6.2	15.1	13.2	10.6	9.4 – 11.0	7.7 - 8.4
C	SMTS	30x	2.39	9.2	15.1	13.6	12.2	-	-
F	Parabolic mirror	6x	2.64	14.2	15.4	14.3	13.4	9 – 13	6.9 - 9.2

* Notes:

- The spreadsheet c/kWh is for a good site (Almeria), and is a comparative number: it includes cells, optics, housing, structure, tracking, and manufacture, but does not include power conditioning, land or overheads. The comparable figure for a flat array is 18.1 c/kWh.
- The spreadsheet efficiency is a spot (i.e. instantaneous) value. The annual efficiency assumed is sometimes lower due to tracking and other losses. The figures are normalised for cells at 25°C, because this is the standard convention for conventional planar arrays, and do not include the 'end losses' of the linear systems, as these reflect each system's physical shape, rather than its cell and optical performance.
- The measured efficiencies are:
  - Best Module: the better, or best, of the prototype modules,
  - Collector: the complete prototype collector,
  - ZSW spot: typical spot efficiencies from the ZSW field test results.

These three efficiencies are also for cells at 25°C, and exclude 'end losses', and thus can be compared with the original 'spreadsheet' estimate.

- The final efficiency ('ZSW long') is calculated from the total power output from each collector during its period of testing at the ZSW test site, divided by the total of the beam radiation normal to that collector's aperture over the same period. It has not been adjusted back to 25°C, nor are end losses subtracted, so it is not comparable with the figures in the other columns. However, this figure can be combined with the annual energy incident on each of the collector types to indicate that system's typical long-term output under field conditions.

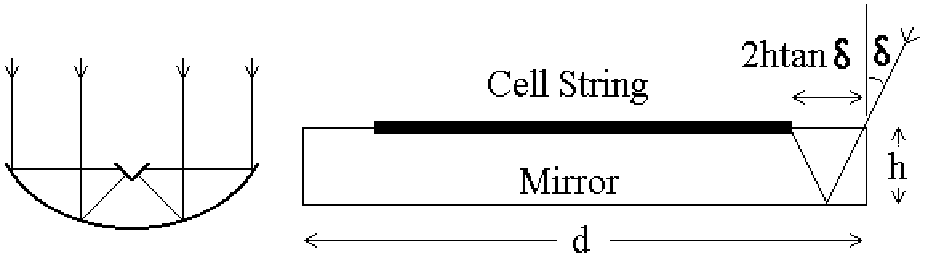

Figure 1. Shading loss: the cell string has to be shorter than the collector.

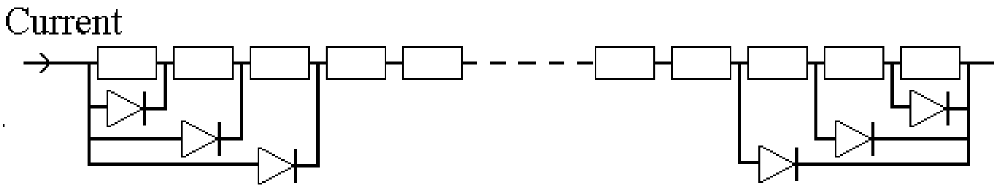

Figure 2. The longer cell string with bypass diodes.

Figure 3. Collector **A**. Multiple point focus Fresnel lenses, mounted in gimbals, with closed-loop tracking about both axes.

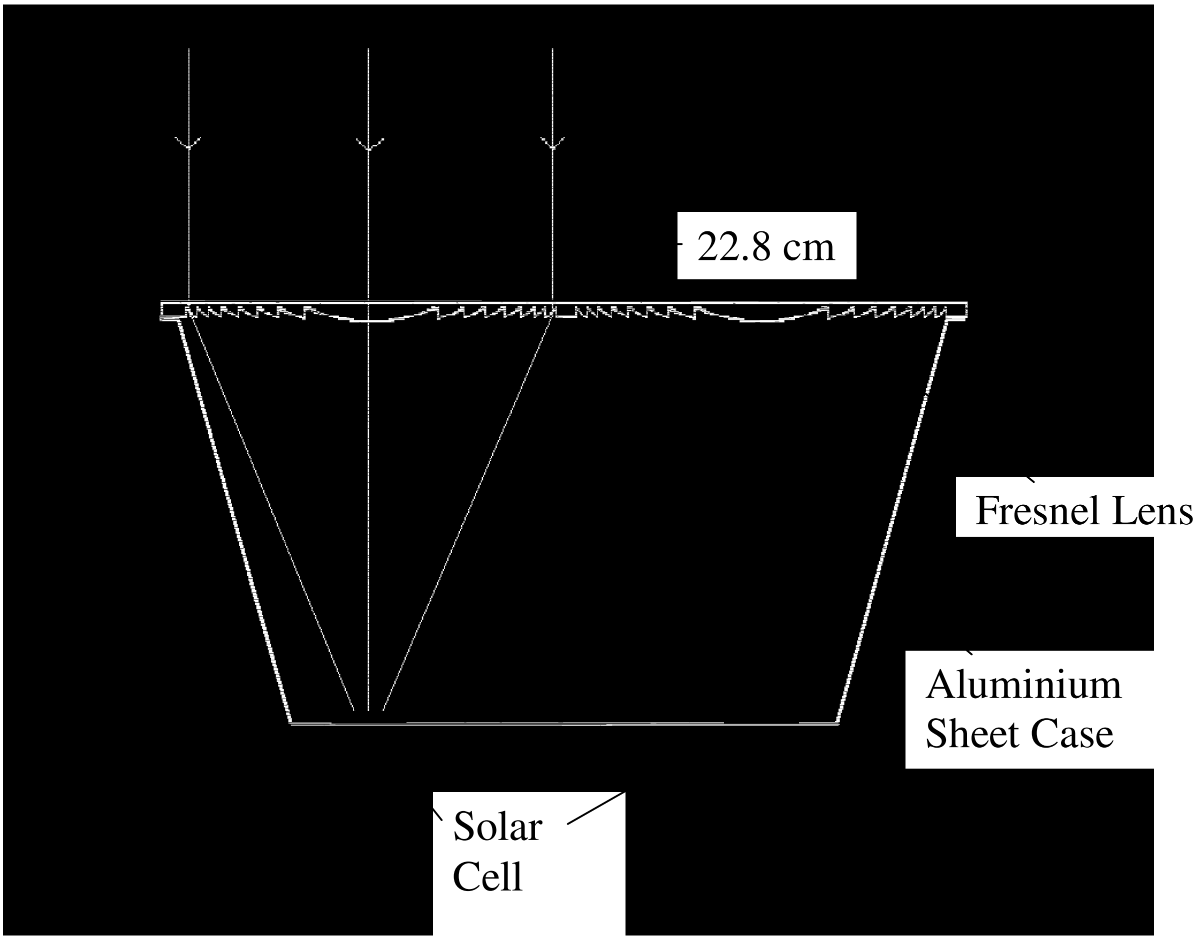

Figure 4. Cross-section of one module of collector **A2**, using point focus Fresnel lenses.

Figure 5. Collector **B**. Multiple cylindrical semi-parabolic mirrors, tracking about a polar axis.

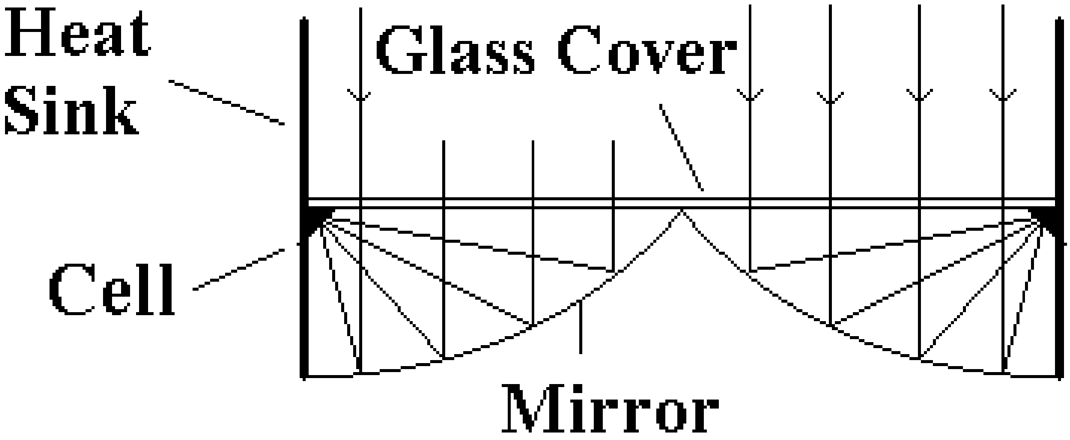

Figure 6. Cross-section of one module of collector **B**.

Figure 7. Collector **C**. The single-mirror two-stage collector, tracking about a polar axis.

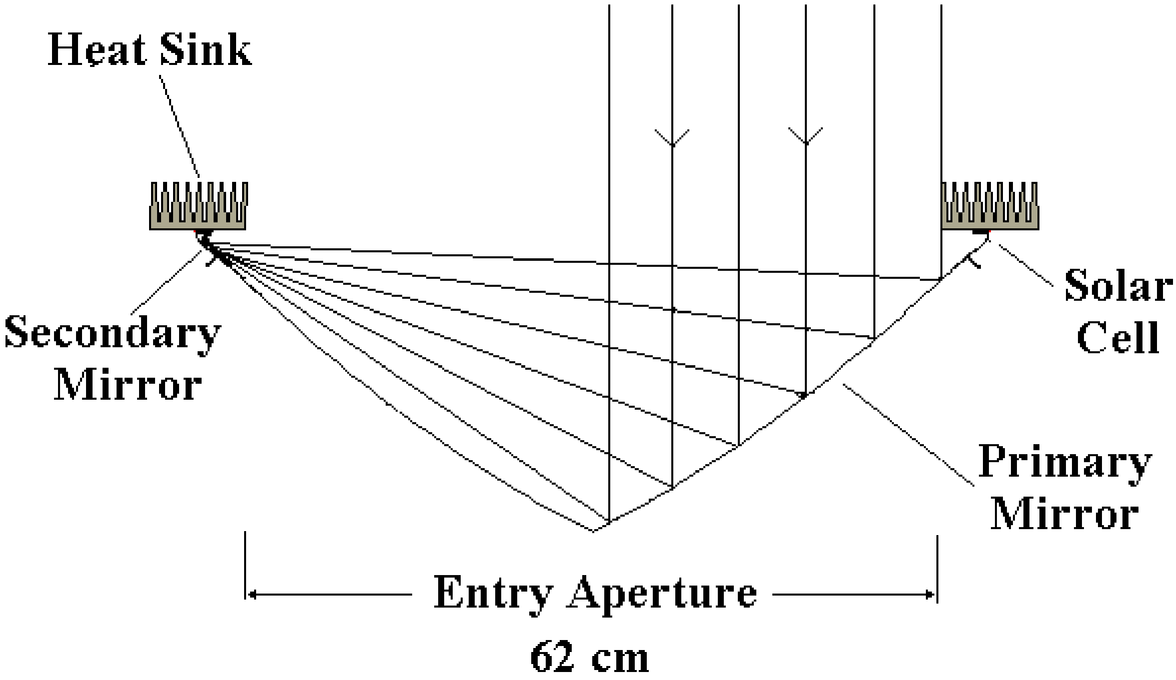

Figure 8. Cross-section of one module of collector **C**, the SMTS collector.

Figure 9. Collector **F**. Multiple cylindrical semi-parabolic mirrors, moved manually every day about an E-W axis.

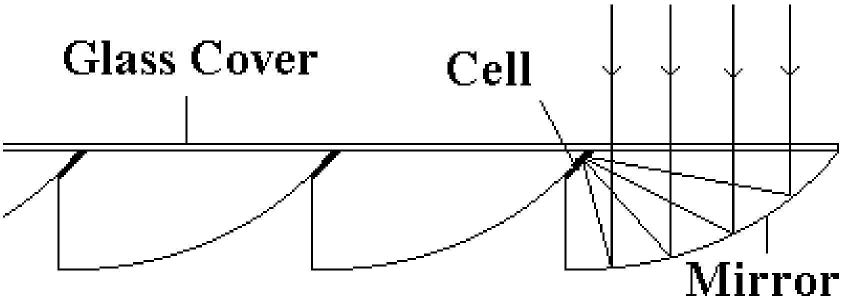

Figure 10. Cross-section of three modules of collector **F**.

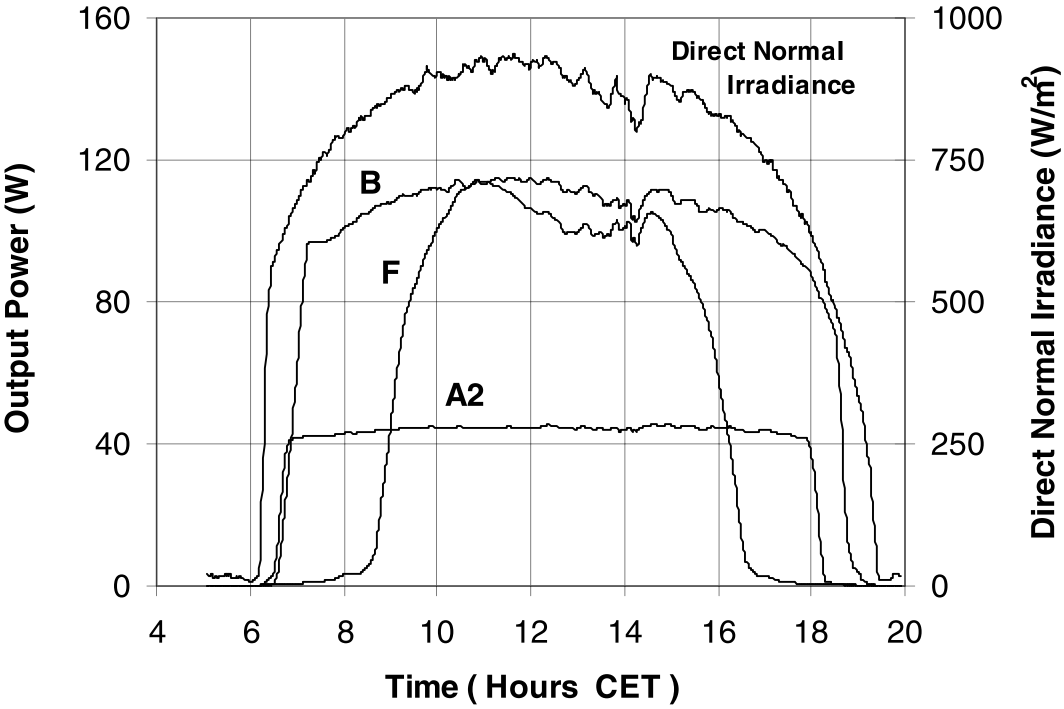

Figure 11. Test results for a clear summer day, 8th August 1998. The curves show the direct normal irradiance, and the output powers from collectors **A2**, **B** and **F**.