Dish Systems for CSP

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Abstract

Parabolic dish technology, for concentrating solar power (CSP) applications, has been continuously modified and improved since the pioneering work in the 1970s. Best practise dishes now have features such as lightweight structure, balanced design, high-quality, low-cost mirror panels, and can be deployed rapidly with little in-field labour. This review focusses on the evolution of dish design, by examining features such as mode of tracking, structure and mirror design, for a wide selection of CSP dish examples. The review includes a brief summary of power generation options – both on-dish and central plant – as well as a discussion about options for storage and hybridisation.

Keywords

Parabolic; dish; CSP; structure; mirror; tracking

1 INTRODUCTION

Parabolic dishes are commonly accepted as the most efficient concentrating solar power (CSP) technology for the conversion of solar energy into electric or chemical energy. For this reason, the promise of dish concentrators has long been recognised. John Ericsson is often acknowledged as the first person to couple a parabolic dish with an energy conversion system (the Stirling engine) [1], and he developed and tested several prototypes in the 1880s. However, despite his enthusiasm for the "sun-motor", he noted with some prescience: "the fact is … that although the heat is obtained for nothing, so extensive, costly, and complex is the concentration apparatus that *solar steam* is many times more costly than steam produced by burning coal" [2]. Ericsson predicted that although "the sun-motor is nearer perfection than the steam-engine ... until the coal mines are exhausted its value will not be fully acknowledged".

It was concern not about coal but about oil that sparked renewed interest in dish collectors to produce energy following the oil crisis in 1973. In the USA, federal laboratories became involved in CSP research [3],and private companies began to invest, both large (e.g. General Electric, Ford) and small (e.g. Omnium-G), supported by generous research and commercialisation funding. Parallel dish development programs began in Australia, France, Germany and parts of the Middle East. In the early 1980s the US budget for solar research was cut drastically under the Reagan administration as energy concerns dissipated, and after 1985-1986, dish commercialisation efforts practically halted for a period of about 10 years [4], but the development effort still continued. During the 1990s, dish commercialisation efforts began to rekindle, with companies like Cummins Power Generation and SAIC. Since the turn of the century, a host of start-up companies have attempted to commercialise dish technologies (e.g. Stirling Energy Systems, Solar Systems, Wizard Power, HelioFocus, Southwest

40　Solar, Infinia), but it has not been easy, with strong competition from other renewable technologies
41　and a difficult financial climate.

42　Ericsson could not predict that well before coal reserves were depleted, concern about global
43　warming (primarily due to the burning of coal) would take over as the main driver for the uptake of
44　solar energy. But nonetheless, nearly 130 years later, his observation about the cost of the
45　"concentration apparatus" remains true as economic not technical barriers limit the widespread
46　uptake of dish (and more broadly CSP) technologies.

47　Over the years, several excellent reviews have been made solar parabolic dish developments [5-9],
48　most with a focus on dish-Stirling systems. In this review, we focus primarily on the evolution of the
49　parabolic dish design. A very brief summary of options for dish power conversion units (PCUs) and
50　energy storage/hybridisation options is included for completeness.

2　PARABOLIC DISH DESCRIPTION

52　A parabolic dish has several key sub-components, described here as the *reflector*, *support structure,*
53　*tracking system, foundations*, *receiver* and *receiver support*.

54　The optical surface of the *reflector* is a truncated paraboloid, the shape obtained by rotating a
55　parabola about its axis. It is a continuous, or faceted, mirrored surface with a single focal point. The
56　reflector must be rotated about two-axes to point directly towards the sun always during operation.
57　The reflector is also a structural component, as it must maintain optical accuracy and structural
58　integrity under wind and gravitational loads while in different orientations. A parabolic dish also has
59　a *support structure*, *tracking system* and *foundations* to facilitate the movement of the reflector, and
60　to anchor it to the ground.

61　Located at (or near) the focal point of the reflector is the *receiver,* held up by the *receiver support.* At
62　the receiver, the radiative energy of the concentrated light is converted to thermal (or chemical)
63　energy in a heat transfer fluid. Usually the energy conversion is indirect via the metal surfaces of a
64　tubular receiver. However, alternative receiver configurations and other modes of heat exchange,
65　such as direct absorption by particles, are possible.

66　The heat transfer fluid may be the working fluid in a power cycle located at the receiver, such as for
67　a Stirling engine, or it may be used to transport energy to the ground for a centralised power cycle
68　(e.g. a steam engine or Rankine cycle power block). The heat transfer fluid may also be used to
69　charge a thermal energy storage system or for industrial process heat. Alternatively, receivers may
70　be designed to operate as chemical reactors, with the products of the reaction used for
71　thermochemical processes such as chemical energy storage, production of synthetic fuels and
72　minerals processing.

3　EARLY DISH DEVELOPMENTS

74　Funding in the US was particularly strong during the 1970s [4] and dish development was
75　consequently driven by the US. The Solar Total Energy Project (STEP) was one of the earliest dish
76　development projects, and in this project many fundamental aspects of dish design were analysed.
77　From 1975 the Jet Propulsion Laboratory (JPL) began research into distributed CSP systems [3, 10],
78　and by the late 1970s a dedicated parabolic dish development project was underway. This included

79 both parabolic dish and mirror panel technologies, as well as adaption of power conversion units for
80 dishes, including Brayton, Stirling and organic Rankine cycles.

81 In the late 1970s a test site was established by JPL at Edwards Air Force Base in the Californian
82 Mojave Desert [11]. A number of parabolic dishes were procured from private companies, including
83 a dish from Omnium-G §5.5 and two so-called "Test Bed Concentrators" §5.6, which were adapted
84 from existing satellite antennae designs, but incorporating JPL's newly developed spherical mirror
85 panels [12, 13]. These prototype dishes had excellent optical performance, and were the work
86 horses for initial tests of engines, materials and the many subcomponents that make up a dish [14].

87 In France, the thermo-helio-electricity-kW (THEK) program was started in 1975 to develop parabolic
88 dish power plants for a range of scales, at temperatures up to 325°C [15]. Two different dishes were
89 constructed during the period 1976-79 (THEK 1&2 §5.2).

90 However, relatively early in the parabolic dish development program it was realised that, despite
91 plenty of previous experience with dish antennae for space tracking, there was a different cost and
92 performance paradigm for design of a solar concentrator. JPL coordinated efforts to develop 'low
93 cost' dishes, initiating the development of the so-called Parabolic Dish Number 1 and 2 (PDC-1 §5.9
94 and PDC-2 §5.10). The main companies involved – General Electric and Ford – were large
95 corporations experienced with mass production techniques. Zimmerman [16] of General Electric,
96 noted the following three objectives:

    1. Establish a design that can be optimised for solar applications. Zimmerman noted that most
97   previous designs were derived from communication and radio frequency antennae, which
98   had various features not necessary for solar applications.
99
100 2. Maximise the performance-to-cost ratio. In other words, every additional dollar spent on
101   improving performance needed to be justified with cost-benefit analysis.
102 3. Select approaches to the subsystem and component designs that were compatible with,
103   and derived from, commercially available manufacturing techniques. Zimmerman noted
104   that labour costs for fabrication needed to be a small component of overall costs.

105 The trade-off between cost and optical quality is complex, as was clearly identified by Truscello very
106 early on, in 1979 [17]. He noted "that optical quality considers all factors that influence the size and
107 location of the solar image such as surface inaccuracies, surface reflectivity and pointing errors.
108 Moreover, the collector cost must consider all factors such as cost of surface, substrate, structure,
109 tracking mechanisms and bearings as well as the cost of the receiver." As he also noted, "the
110 problem becomes even more complex when the issues of receiver temperature and power
111 conversion are introduced. A higher temperature may result in greater system performance because
112 of the increased efficiency of the power conversion unit. However, to collect at higher temperatures,
113 better quality optics are needed which increase collector costs". These prescient observations
114 remain highly relevant today, as discussed later (§6.5).

115 From the early 1980s low-cost design was always a core objective for dishes, and dishes such as
116 Vanguard (§5.12) and McDonnell Douglass (§5.13) built upon the knowledge gained from the PDC-1
117 and PDC-2 projects, albeit with many new design features. Two main styles of dishes emerged from
118 these developments: glass-faceted concentrators and full-surface paraboloid concentrators [7].
119 From 1984, management of the US dish program shifted from JPL to Sandia National Laboratories.
120 The effort to reduce cost also led to some very novel concepts, and at the forefront was another
121 style of dish, the so-called stretched-membrane concentrator. Although the concept had been
122 around since the early 1970s (Bomin Solar §5.1), development of stretched membrane dishes

123 accelerated in the mid-1980s. schlaich bergermann und partners (SBP) built its first three stretched
124 membrane dish prototypes in 1983, deployed first in Germany, then in Saudi Arabia. At 17m
125 diameter, these were large compared to other dishes at the time. A notable project in the US was
126 the independently financed 700 dish 'Solar Plant 1', installed in 1984 by LaJet (§5.14). The LaJet
127 dishes used the stretched-membrane concept but with multiple facets. At this time, the U.S.
128 Department of Energy (DOE), through Sandia National Laboratories and NREL (then SERI) with
129 private industry partners also began to develop stretched-membrane concepts, initially for heliostats
130 [18, 19], but also for dishes from 1987 (SKI §5.17 and SAIC §5.19).

131 Another concept that was explored in the effort to achieve low cost was the so-called Stationary
132 Reflector/Tracking Absorber solar collector (SRTA). In this concept, the reflector is a stationary
133 segment of a sphere, and the absorber must be moved so its axis is always aligned with solar rays
134 passing through the sphere centre [20]. The tracking requires motion of the absorber about two axes
135 that intersect at the sphere centre. The receiver is an external, cylindrical linear receiver aligned to
136 this axis. Cost advantages from the fixed reflector trade against performance disadvantages due to
137 the higher cosine losses and lower concentration ratio. A small scale system was tested by E-systems
138 [20], and then demonstrated at larger scale in the Crosbyton project (§5.8), and later in Auroville,
139 India [21]. A converse concept is the so-called Scheffler dish [22], where the focus is fixed and the
140 reflector is a segment of a paraboloid with daily east-west tracking, and slow seasonal adjustment of
141 declination. The tracking concept was described by Bomin Solar §5.1 in the early 1980s [23], but
142 reintroduced in the present form by Wolfgang Scheffler in 2006 for solar cooking applications. The
143 Thermax dish is based on this concept (§5.32).

144 As an alternative to a dish, a concentrator may utilise a lens. This has been particularly popular for
145 concentrating photovoltaic applications [24] because the conversion device can be a single cell and
146 the Fresnel lens can therefore be small . Multifaceted lenses are relatively simple to make, and can
147 be mounted on a single, larger solar tracking structure. For solar thermal applications, typically the
148 receiver is large, and therefore lenses need to be large and are less suited to existing lens
149 manufacturing methods. Also, the lens is more sensitive to slope errors, suffers chromatic
150 aberration, and is limited to a longer focal length to diameter ratio than mirrors (necessitating a
151 larger structure). However, advantages are that the receiver can be close to the ground and both it
152 and its supports do not block the sunlight [5]. E-systems (later renamed Entech) developed a
153 conceptual design for an 11 m diameter concentrator based on a convex, dome-shaped acrylic
154 Fresnel lens consisting of ten conical ring segments [25].

155 # 4 POWER GENERATION

156 The evolution of dishes is intrinsically linked to the evolution of power conversion units and solar
157 receivers, which is a substantial topic for review and not attempted in the present work. However, a
158 brief summary of power generation options is provided as context for the dish review.

159 Many different power conversion cycles have been considered for use with parabolic dish
160 technology, with different working fluids. Dish mounted options investigated include organic
161 Rankine cycles turbines with toluene, Stirling engines with hydrogen or helium, and open and closed
162 air Brayton cycles. Dishes have also been used with concentrating photovoltaic modules. Ground
163 mounted options investigated include power cycles suited to small power stations, such as Rankine
164 cycle engines with steam, as well as power cycles suited to large power stations, such as
165 conventional Rankine cycle steam turbines. Ground mounted systems require additional field piping

166 networks and flexible or rotating couplings on the dishes, but do allow for large, centralised power
167 blocks. For much of the history of dish development, dish-mounted power conversion units, or so-
168 called 'dish-electric' systems, were considered attractive because of the modularity offered
169 compared to parabolic trough and central receiver systems [6]. Modularity meant flexible
170 deployment of dish-electric systems in either small or large installations, and opened mass-
171 production possibilities. However, modularity and scalability is also a feature of photovoltaic (PV)
172 technology and today dish-electric systems need to contend with the low cost of PV. Thermal and
173 thermo-chemical storage options, prevalent in other areas of CSP, may lead to a competitive edge
174 over PV.

4.1   Stirling Engines

176 Stirling engines are attractive for dish-electric systems because of their high power conversion
177 efficiency (30-45%) at small scale [26], with peak solar-to-electric efficiency exceeding 30% (Table 1).
178 The Stirling cycle is in general well matched to the characteristics of dish operation. Concentrated
179 solar flux from dishes can provide isothermal, high-temperature (typically 650°C-800°C) heat with
180 good efficiency. Stirling engines have been both coupled directly to dishes [27] or indirectly via a
181 sodium heat pipe [28]. Hybrid solar and gas systems have been tested to allow higher capacity
182 factors and better performance during solar transients [27]. The main Stirling engines developments
183 for dishes to-date are summarised as follows:

184 • The 25 kW 4-95 Mk II Stirling engine from United Stirling AB (USAB, a subsidiary of Kockums AB
185   of Sweden) [29]. It was developed and tested with the TBC §5.6, Vanguard §5.12, MDAC §5.13,
186   SES §5.20 and Ripasso §5.29 dishes, including the original Mk II engine and derivatives. All four
187   records reported in Table 1 used versions of this engine.
188 • The 10kW SOLO V-160, which originated from a different subsidiary of Kockums, Stirling Power
189   Systems (SPS) [30], and was developed in partnership with Solo Kleinmotoren GmbH, later Solo
190   Stirling GmbH. It was tested by schlaich, bergermann und partner (SBP) on the DISTAL/Eurodish
191   systems §5.16, by Sandia on the ADDS project §5.18 and is currently being developed by
192   Cleanergy §5.31.
193 • The 22 kW STM 120 from Stirling Thermal Motors (STM) (now Stirling Power), that was deployed
194   on the SAIC SunDish §5.19.
195 • The 3 kWe Stirling engine, developed by Infinia for its PowerDish system §5.27.

196 *Table 1. Best reported solar-to-electric efficiency for dish-Stirling systems for instantaneous peak*
197 *conditions.*

Dish system	Original Stirling engine*	Gross efficiency (at generator)	Net efficiency (less parasitics)	Year
Vanguard §5.12 [31].	USAB 4-95	31.6%	29.4%	1984
MDAC §5.13 [29]	USAB 4-95	31.4%	30.0%	1985
SES MPP §5.20 [32]	USAB 4-95	-	31.25%	2008
Ripasso §5.29 [33]	USAB 4-95	-	32%	2011

198   * noting the engines were developed and improved, and often re-named, over time

4.2   Steam engines

Both dish mounted and ground mounted steam engines have been investigated for parabolic dish applications. Jay Carter Enterprises [34] tested ground mounted prototypes at power levels of 80 kWth and measured efficiency about 19-20%. Their study of a dish mounted option found that a two-cylinder engine with input steam at 677°C efficiency could approach 30% efficiency. Very similar results at high temperature were predicted by Foster-Miller Associates [35]. ANU tested a ground-mounted steam engine, which was a modified Lister 3-cylinder diesel engine, connected to network of 14 dishes at its White Cliffs project [36] §5.11, demonstrating engine efficiency of 21.9%. A similar 4-cylinder ground mounted steam engine was also tested by PKI/ANU at Sandia §5.15. No dish mounted steam engine has ever been tested.

4.3   Steam generation

Direct steam generation (DSG) receivers have been developed for dishes designed to be connected small, off-grid engines and to large, on-grid steam power plants. DSG receivers are typically single-pass helical coils that form a cavity, although with various geometrical configurations. An early development was in 1980 by Garrett AiResearch, who constructed and tested a steam receiver (Figure 1a) on a TBC dish §5.6, showing thermal efficiency in the range 80-88%[1] [37]. At White Cliffs §5.11 steam receivers with a range of geometries were tested, with best thermal efficiency for a trapezoidal cavity of around 93% at 500°C at the outlet. The ANU SG3 Big Dish steam receiver §5.21 was cylindrical top-hat cavity, and incorporated a shallow frustum pre-heat section in lieu of a passive heat shield. The ANU SG4 Big Dish steam receiver §5.22 had a similar configuration but re-designed geometry for the improved optics of the SG4 dish (Figure 1b), and achieved 97.1% thermal efficiency in on-sun tests for steam >500°C [38]. Thermal oil has been used for indirect steam generation, albeit for power generation with additional exergetic losses associated the oil-to-steam heat exchangers. For example, oil was used at the Shenendoah plant §5.4, using a cavity receiver with a similar geometric configuration to the steam receivers discussed above (Figure 1c). However, oil is limited to temperatures of around 390°C. Air has been used as the heat transfer fluid (HTF) with dishes, originally for the Ominium-G dish §5.5 and more recently for the HelioFocus dish §5.25.
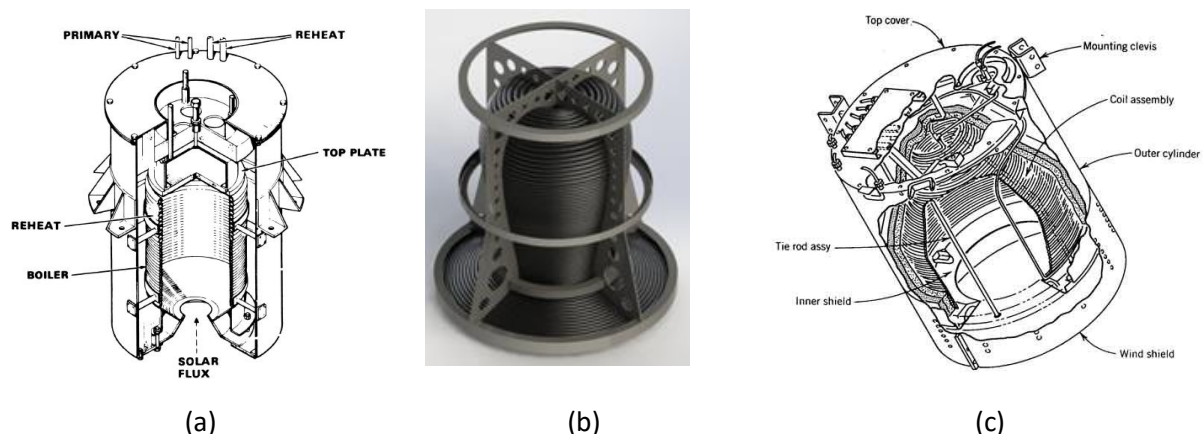

(a)   (b)   (c)

Figure 1. Steam receivers from (a) Garrett [6] and (b) the ANU SG4 Big Dish [38], and an oil receiver from Shenandoah [39, 40]

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[1] Temperature of tests corresponding to this range not given.

4.4 Organic Rankine cycles

Receivers that integrated an organic Rankine cycle (ORC) were developed in the US dish program in the late 1970s – early 1980s, and tested on the TBC §5.6 and PDC-1 §5.9 dishes. The receiver development was led by Ford Aerospace and Communications Corporation [41], with Barber Nichols designing and building the ORC unit. Toluene is circulated in a hermetically-sealed closed loop system, and vapour at about 400°C drives the turbine-alternator-pump assembly at speeds up to 60,000 rpm. The turbine speed allows the turbo-machinery to be very compact. Measured efficiency during testing in 1982 was 22.9%.

4.5 Air Brayton

Development of air Brayton engines intended for mounting on a dish was extensively funded under the US dish program, as at the time they were considered lower risk ("first-generation") than Stirling engine developments ("second-generation") [6]. As it eventuated, Stirling engines proved more efficient, and technical challenges were more rapidly overcome to achieve working prototypes for on-sun testing on dishes. There have been only two successful on-sun dish-Brayton demonstrations [42]. The first, in 1984, was led by Sanders Associates, using a microturbine designed by Allied Signal (Torrance, CA), a Lajet 460 dish §5.14, and a Sanders receiver. Garrett AiResearch and Sanders Associates also cooperated to develop a regenerated air Brayton engine during the early 1980s [43] but initial on-sun tests at the Sandia TBC dishes in 1985 were reported as unsuccessful due to rotor-dynamic bearing problems. The second on-sun test was in 2011, when Brayton Energy and Southwest Solar Technologies briefly tested their dish-Brayton system before terminating their work in this area.

4.6 Concentrator photovoltaic (CPV)

CPV is dominated by refractive optics concentrators (lens) but there have been several dish CPV systems, notably Solar Systems (§5.23). Other CPV dish systems have been smaller, such as those from Zenith Solar [44] and REhnu [45].   In 2013, Solar Systems claimed approximately 30% solar-to-electric (AC) efficiency using 40% efficiency solar cells for a complete power plant system [46], comparable efficiency to dish-Stirling systems listed in Table 1 . Since then concentrator cell efficiency has continued to improve, with the record for a III-V multi-junction solar cell now 46.0% at 500 suns [24]. It is critically important to achieve a uniform flux profile for good performance of a CPV dish system (typically around 500 suns), which is an important design consideration for a CPV dish.

4.7 Thermochemical

Solar thermochemical processes for producing fuels and for chemical energy storage typically require very high temperature, and therefore for some processes are well suited to dishes. Most testing has been in laboratories with solar furnaces or on central towers. However, there are some dish examples. The Australian National University carried out dissociation of ammonia using a 20 m^2 dish (a twin to those at White Cliffs §5.11) as part of the investigation of an ammonia-based energy storage system [47] (Figure 2a). Steam reforming of methane has been demonstrated on dishes, in 2002, by CSIRO at Lucas Heights on a Solar Systems dish [48] and more recently, in 2011, by Pacific Northwest National Laboratory (PNNL) and Infinia [49] (Figure 2b). Solar-to-chemical conversion efficiency of 69% was demonstrated [50].
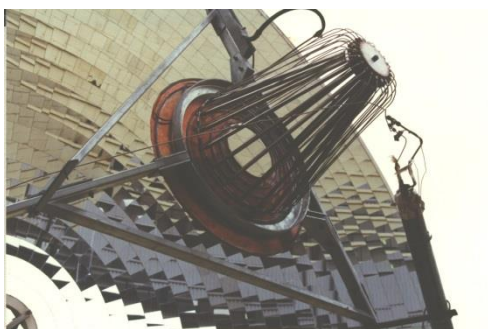
(a)   (b)

Figure 2. (a) Ammonia reactor on the ANU 20 m^2 dish (shown with insulation removed), and (b)
steam reforming reactor in conjunction with microchannel heat exchangers on the Infinia
PowerDish. Photos: ANU, Pacific Northwest National Laboratory.


5   DISHES PAST AND PRESENT

The list of dishes described below have all had prototypes built at full scale, and are intended as a
guide to the evolution of the technology. However, it is by no means a complete list of all dishes.

5.1   Bomin Solar [23, 51, 52]

Bomin Solar GmbH pioneered the concept of using large foil-membrane mirrors for solar
concentration in the early 1970s. They developed a parabolic dish mirror by stretching plane,
metallised plastic membranes over hollow, drum shaped structures. By forming pneumatically the
membrane with slight over or under pressures, they achieved concentration ratios over 1000. To
achieve a perfect parabolic shape, a method was developed to apply an anisotropic pre-stretching of
the membrane. The dish was surrounded by an external light-weight dome structure to protect the
membrane. Bomin Solar later (in 1990) developed a fixed-focus collector (Figure 3a), based on
rotating a segment of a paraboloid around the focal point. The dish concept, shown in Figure 3b, was
first described by Bomin in the early 1980s [23],

(a)   (b)
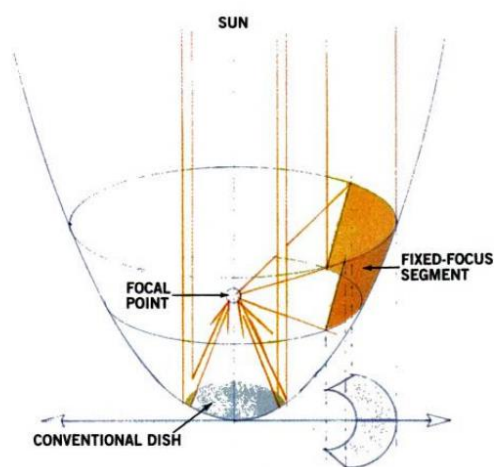
285 *Figure 3. (a) Bomin Solar's fixed-focus collector prototype and (b) diagram demonstrating the fixed-*
286 *focus dish concept [52].*

5.2   THEK 1 & 2 [15, 53]

288 In the first phase of the French thermo-helio-electricity-kW program (THEK 1), four 50 m^2 dishes
289 were tested, two each of the designs shown in Figure 4a. The dishes were located at the Centre
290 d'Essais Solaires de Sant-Chamas, near Marseille. The reflectors were constructed from 750 flat
291 triangular glass mirrors bonded to fibreglass, but two very different tracking styles were tested. The
292 receivers were a mono-tube coil with thermal oil as the heat transfer fluid at outlet temperature
293 325°C. Optical and thermal efficiency of these dishes were both rather low. In the second phase
294 (THEK 2), the focus was on even lower temperature industrial process heat. An eight-dish
295 demonstration plant was constructed with saturated steam at up to 260°C as the heat transfer fluid
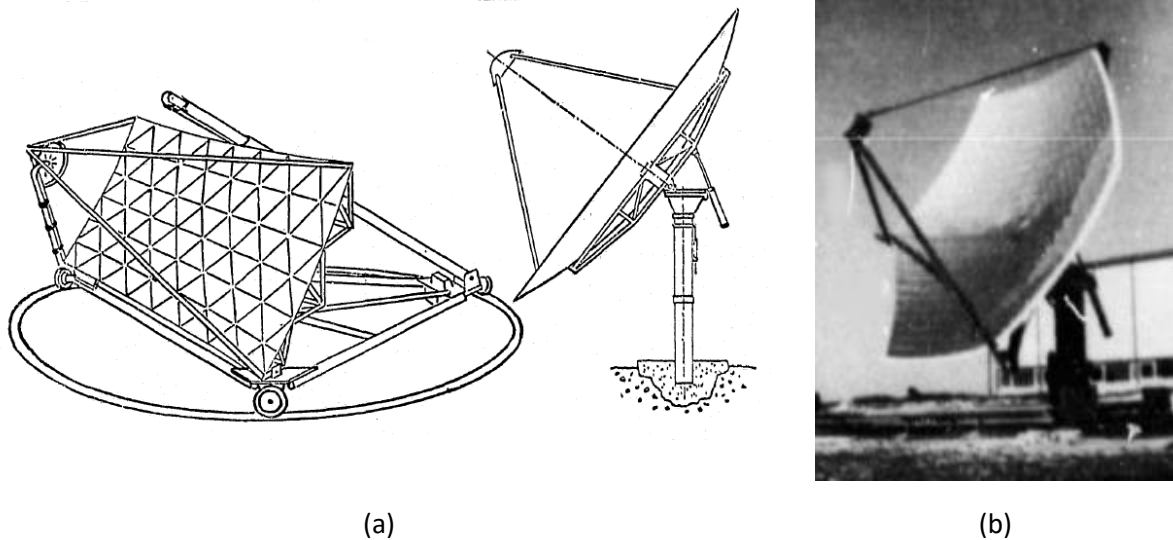296 (Figure 4b).

297

(a)   (b)

298 *Figure 4. (a) THEK 1 dish designs, and (b) a THEK 2 dish [15].*

5.3   Raytheon [6]

300 The Raytheon dish (Figure 5) was evaluated as part of the Solar Total Energy Project (STEP) program.
301 It was a 6.7 m diameter dish, consisting of spherical, heat sagged mirror segments. The tracking was
302 azimuth-elevation.

303

304 *Figure 5. The Raytheon concentrator [6].*

5.4   Shenandoah [26, 39, 40, 54-56]

306 The Solar Total Energy Project (STEP) at Shenandoah, Georgia, was a large industrial application of
307 solar cogeneration at a garment plant, that operated between 1982 and 1991. The 7m diameter dish
308 (Figure 6a) deployed at Shenandoah was designed by General Electric Corporation and was
309 manufactured by Solar Kinetics, Inc. The reflector was assembled from 21 die-stamped aluminium
310 gores (or "petal" shaped segment), bolted to supporting sheet metal rib, and held together by a
311 steel hub. An acrylic aluminised film from 3M was applied (protected by an opaque film) to the flat
312 sheet blanks prior to forming the gores to shape. The tracking system had polar and declination axes
313 of rotation and was supported on a steel tripod structure mounted on concrete piers. The reflector
314 structure was counter-weighted about the polar axis by a rotating concrete yoke. The solar field
315 consisted of 114 dishes, each 7m diameter, producing heat in receivers using a synthetic oil heat
316 transfer fluid in a cavity coil type receiver (Figure 6,c).

317 The Shenandoah receiver was a cavity-type receiver with a stainless steel coil-type heat exchanger
318 [39, 40]. The oil was heated to 399°C and used to generate steam for powering a Rankine steam
319 turbine-generator, with low pressure process steam extracted for pressing clothes and powering an
320 absorption chiller. The plant incorporated buffer energy storage, with a thermocline oil tank to allow
321 continuous operation during short-term solar transients.
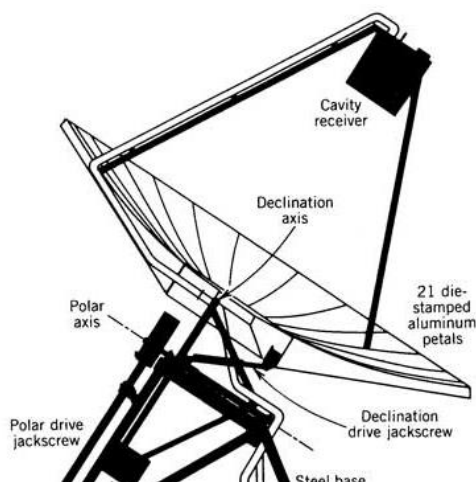
(b)

(a)

(c)

Figure 6. The Shenandoah dish shown in (a) schematic view [56] and (b,c) as installed.

5.5 Omnium-G [11, 57]

One of the earliest private companies to develop parabolic dish technologies was US company Omnium-G, which installed its first parabolic dish in Golden, Colorado, in May 1978[2] [57], and in the following few years installed a further thirteen concentrators around the world. The dish is a full-surface paraboloid with polished aluminium gores for the reflective surface (Figure 7). Two types of receivers were developed, a direct steam generation receiver at 593°C and an air receiver at up to 980°C.

Figure 7. The Omnium-G parabolic dish collector.

5.6 TBC 1 & 2 [12, 13, 58, 59]

The TBC 1 & 2 dishes were 11m diameter dishes, supplied by E-systems in 1979 and installed at Edwards Air Force Base (Figure 8). The 228 mirror facets, jointly developed with JPL, were made by bonding a second surface mirror to a cellular glass substrate machined to a spherical shape. Cellular glass has a high stiffness-to-weight ratio and a thermal expansion coefficient matched to the glass mirror. The substrate was coated with a protective sealer and painted white. The reflector structure was a radial truss arrangement, an adaption of an antenna designed for the satellite program. The receiver support was bipod type, stabilised laterally with rods. The support structure was a space

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[2] It formed the backdrop when President Carter opened the Solar Energy Research Institute (now National Renewable Energy Laboratory).

340 frame, with a wheel-on-track type azimuth rotation, and a linear elevation drive. In 1984, the TBCs
341 were moved to the Sandia National Laboratories in Albuquerque. In 1993 the mirrors had new thin
342 glass mirrors bonded on top, as they had suffered large areas of silver corrosion. The corrosion was
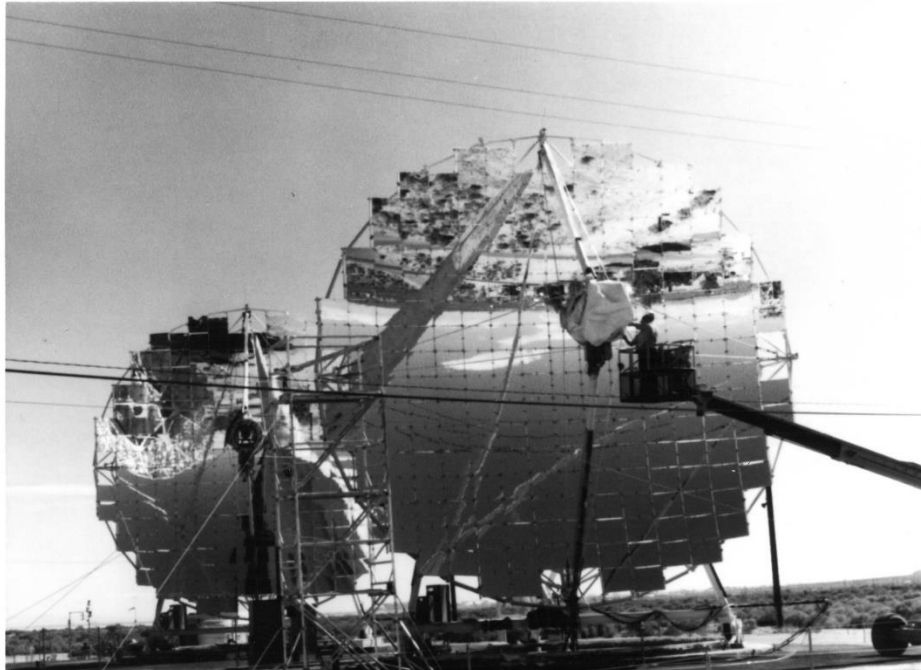343 attributed to poor sealing, and the moisture retaining characteristics of the glass foam substrate.

344

345 *Figure 8. The TBC 1 & 2 collectors installed at Edwards Air Force Base*

5.7 Kuwait dishes [60, 61]

347 Messerschmitt-Boelkow-Blohm, together with the Kuwait Institute for Scientific Research (KISR)
348 developed an 18 m^2 parabolic dish with first tests at KISR in 1979 (Figure 9a). Subsequently 56 dishes
349 were deployed in the desert region of Sulaibyah in Kuwait. The reflector was composed of six
350 reinforced plastic sandwich panels, covered with very small (30 mm x 30 mm) mirror facets. A
351 feature of this dish was that it was designed to rotated about the focal point, thereby avoiding the
352 need for flexible piping to the receiver (Figure 9b). The heat transfer fluid was a synthetic oil
353 (Diphyl), and balance of system incorporated thermal energy storage and an organic Rankine cycle
354 for power generation.

355
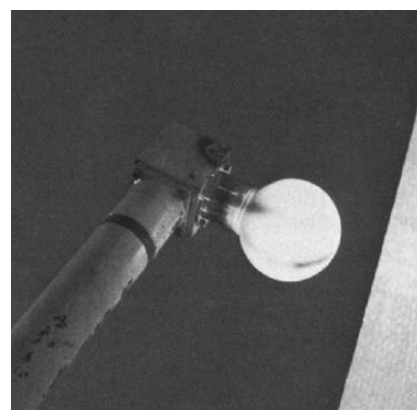
Figure 9 (a) Dishes installed in Sulaibyah, Kuwait; and (b) the fixed focal point oil receiver [61].

5.8   The Crosbyton project [62]

This Crosbyton dish uses the Stationary Reflector/Tracking Absorber (SRTA) concept described earlier (§3). It was installed by the Texas Tech University and E-systems, in Crosbyton, Texas, in 1980 (Figure 10). It had an aperture of 20 m, and was constructed from glass mirror facets stressed to a spherical shape and bonded to paper honeycomb backing structures. The facets were fastened to curved tubular beams. The receiver was counterweighted and swivelled in two axes about a point at the centre of the spherical bowl to track the sun. It was a direct steam receiver, made of an externally illuminated cylindrical coil, with nominal outlet conditions of 540°C and 6.8 MPa.
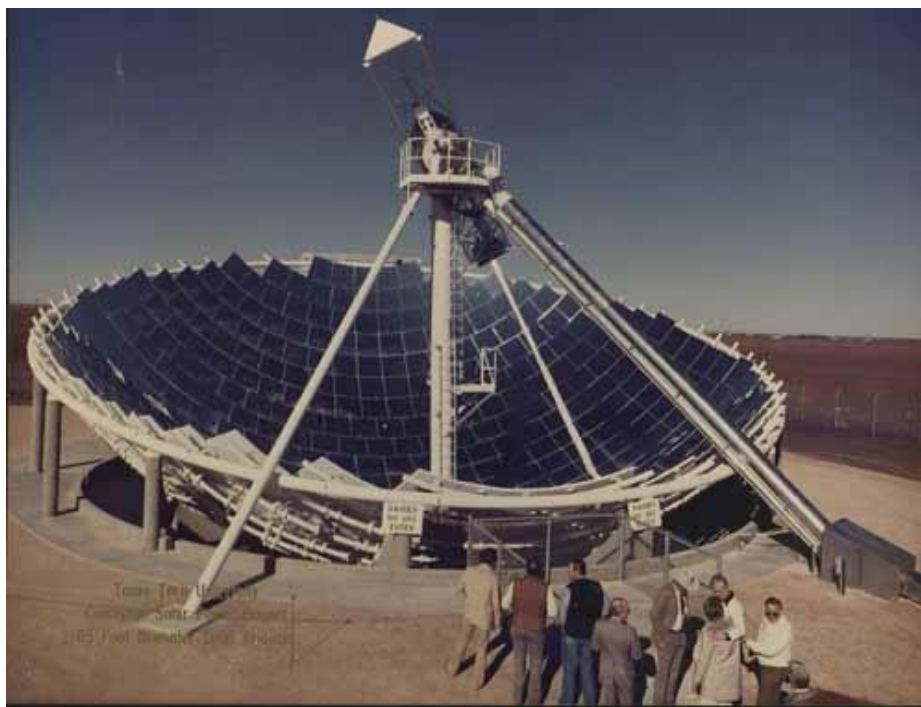
Figure 10. The Crosbyton solar bowl. Source: Texas Tech University

5.9   PDC-1 [16, 26, 63, 64]

Designed by the space division of the General Electric (GE) company, the PDC-1 dish had as key objective engineering for low cost. Significant effort was made by GE to develop high volume tooling and manufacturing processes for the mirror panels, which were a sandwich panel construction of fibreglass and balsa. An aluminised polyester reflective film was then bonded to each panel. The reflector was a full-surface type, with 12 gore panels supported by 12 front-bracing corrugated steel ribs. The reflector was a load bearing structure, and integral to the stiffness and strength of the dish.

The elevation axis pivots were located at the perimeter of the reflector, and held up by a space frame construction. This allowed the reflector a full 180° range of movement, which meant it could be stowed with the mirror facing down. This was useful for mirror cleanliness, protection from hail damage, wind loads reduction and provided maintenance access to the receiver. A semi-circular truss spanned the 180° range between the receiver at the front and a counter-weight at the back of

380 the dish, and was used for rotation of the reflector via a cable-drum arrangement, as well as forming
381 one of three receiver support arms. The azimuth rotation of the supporting space frame structure
382 was by wheels on a rolled I-beam circular track, supported by concrete piers.

383 PDC-1 was installed at the Edwards Air Force Base test site in 1981 (Figure 11). Initially the optical
384 properties of the PDC-1 were much poorer than expected. This was due to thermal expansion
385 coefficient differences between the mirror panels and steel ribs. The panels were installed in very
386 hot weather, and flattened at lower temperatures. This was compounded by some gravitational sag
387 effects, as the panels were installed while the dish was inverted. The panels were removed and
388 reinstalled, resulting in a 3-fold reduction in the spot diameter.

389 The receiver deployed on PDC-1 was designed by Ford Aerospace and Communications Corporation
390 and was a cavity type, direct-heated, once-through monotube boiler with toluene at supercritical
391 pressure (see Figure 11b,c). It was formed by a cylindrical copper shell and back wall with stainless
392 steel tubing brazed to the outside surface, surrounded by insulation [65]. The copper shell had
393 grooves machined into it to match the steel coil, to hold it in place and ensure good thermal contact.
394 In tests in 1982, very good receiver thermal efficiency (radiation reflected to the receiver from the
395 dish / energy absorbed by the fluid) was measured, at 95.2% [66].

396 Barber Nichols designed and built the Organic Rankine Cycle (ORC) unit. Steady state tests were
397 carried out in early 1981, then on-sun tests in late 1981 – early 1982. The complete ORC power unit
398 was operated successfully over a range of operating conditions. Excessive bearing wear was
399 experienced early in testing, but his problem was rectified [67]. Predicted engine efficiency (net dc
400 electrical output / thermal energy input) was about 26%, with relatively good part-load
401 characteristics predicted to benefit annual performance, given the wide variety of solar operating
402 conditions [41]. Measured engine efficiency during testing in 1982 was 22.9%, a few percentage
403 points below prediction attributed to high pressure drop in the regenerator, and energy losses in the
404 feed pump and alternator [68].

(b)

(a)

(c)
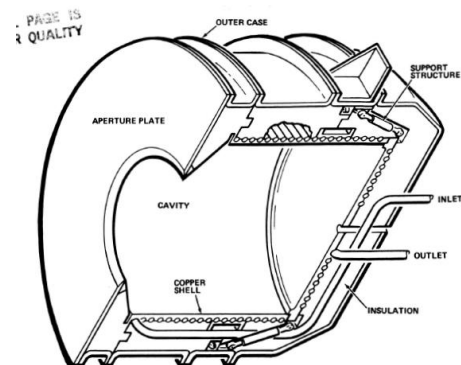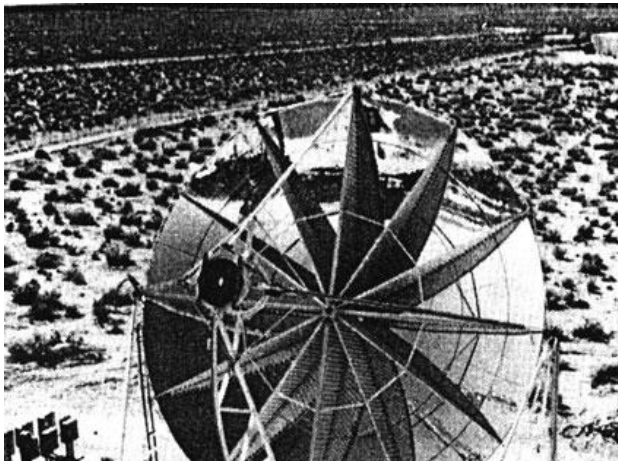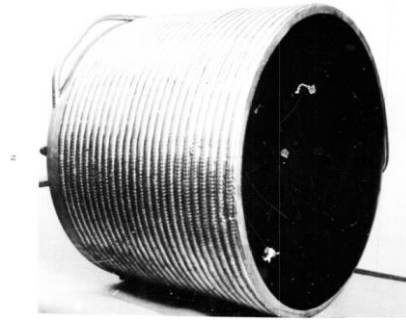
Figure 11. (a) The PDC-1 installed at Edwards Air Force Base [26]; (b) schematic diagram and [6] (c)
photo of the tubular toluene boiler that was attached to the front of the ORC power unit [69].

5.10   PDC-2 [70-72]

The PDC-2 dish was a 12.2m diameter dish developed by Acurex Corporation, as a subcontractor to
Ford Aerospace and Communications Corporation, and was tested at Sandia, Albuquerque. The
reflector comprised 64 inner and outer facets mounted on either side of a ring truss. Acurex
evaluated two mirror panel constructions, one based on thin glass bonded to a compression
moulded composite sheet-rib structure, the other with a construction like that used for the TBCs,
except modified to form a sandwich structure. The cellular glass core (machined to shape) is
sandwiched between thin back silvered mirror glass on the front and unsilvered glass in a narrower
strip on the back. The latter option was selected for the PDC-2 dish. Due to the good structural
properties of the mirror panels, they could be simply supported but partly cantilevered from the ring
truss to minimise the reflector support structure requirements. The ring truss was hinged on the
elevation axis from an intermediate space frame structure. The original PDC-2 design employed a
wide based perimeter drive configuration, but Acurex changed this to a pedestal type configuration,
with azimuth-elevation tracking, to save on site assembly and foundation installation costs.
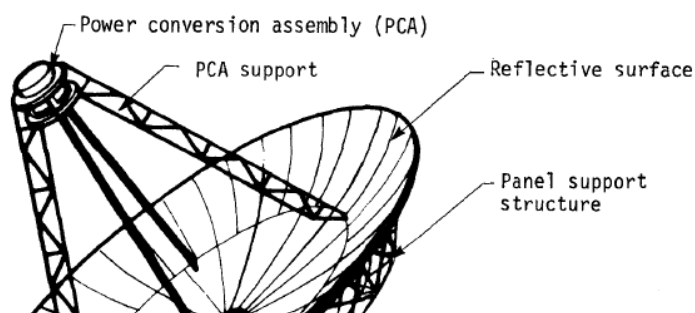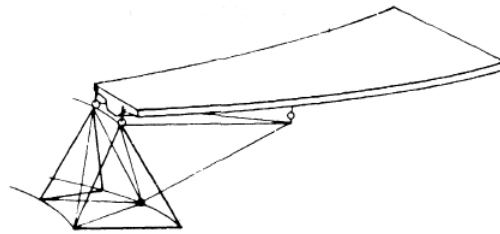
(b)

422   *Figure 12. (a) Schematic diagram of the PDC-2 dish [70] and (b) the mirror facet and ring truss*
423   *connection [72].*

5.11   ANU/White Cliffs [36, 73]

425   The Australian National University (ANU) White Cliffs project was a 14-dish installation built in 1980-
426   81 to provide power to the remote town of White Cliffs in New South Wales (Figure 13a). The dishes
427   were constructed from a 5 m diameter fibreglass shell formed on a mould and tiled with 2300 small
428   planar 2.5 mm thick glass mirror facets, each cut to conform to the paraboloidal shape. Dishes were
429   transported to site as a wide load from Canberra to White Cliffs, with bridge clearance being a key
430   consideration! (Figure 13b). The pedestal support included a novel "pipe-in-pipe" azimuth rotation.
431   The advantage of this system is distribution of overturning loads along the pedestal pipe, rather than
432   a load concentration at a drive at the top of the pedestal. A disadvantage is that that an extra pipe is
433   required within the pedestal.

434   DSG receivers on the dishes provided steam to a modified Lister HR-3 3-cylinder diesel engine.
435   Steam was supplied to a chamber in the head of each cylinder. This adaption approach was to take
436   advantage of the large existing market for diesel engines. The two major areas of development
437   required were in the valve mechanism, and the oil-water treatment. The steam carried some oil
438   droplets, which needed to be removed before the water was recirculated to the collectors. Engine
439   efficiency was measured at 21.9% (415°C, 4.1 MPa). A wide range of steam receiver geometries were
440   tested at White Cliffs, with the Mark 2 and Mark 10 receivers shown in Figure 13c-e. Thermal
441   efficiency (radiation reflected to the receiver from the dish / energy absorbed by the fluid) was
442   approximately 85% and 93% at 500°C steam outlet temperature for these two receivers respectively
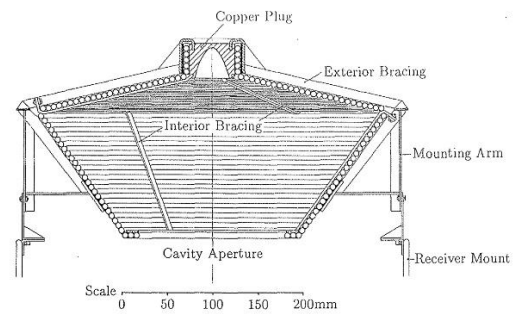443   [73].

(a)
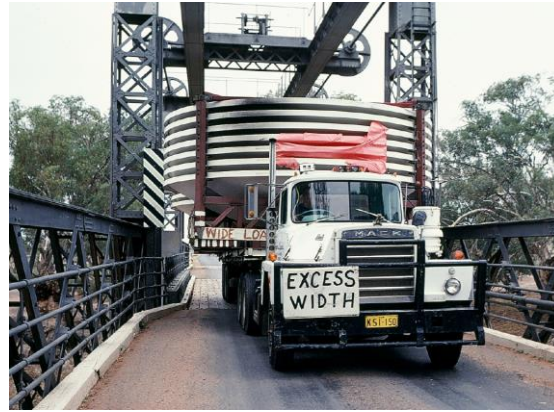
(b)

(c)

(d)

(e)

Figure 13. (a) Dishes at White Cliffs; (b) dishes in transport to site; (c) the Mark 2 receiver on sun; (d) the Mark 10 receiver on sun; and (e) a schematic diagram of the Mark 10 receiver [73]. Photos: S. Kaneff and P. Bannister (ANU)

5.12   Vanguard [7, 31, 74]

In a cooperative effort to commercialise the dish/Stirling technology, Advanco Corporation led a joint private/public team to build upon the JPL work and develop parabolic dish named "Vanguard" (Figure 14a). The dish was made up of 336 mirror facets mounted on a rack and truss structure. The facets were constructed of thin glass mirrors bonded to a spherically ground 50mm thick foam glass substrate. The tracking system had a standard azimuth rotation, but a novel exocentric elevation axis skewed at 45° to pass through the centre of the gimballed mass to maintain the centre of gravity in a horizontal plane and hence minimise torque requirements (Figure 14b). A United Stirling 4-95 Mk II Solar SE engine was mounted on the dish, and it was tested at Rancho Mirage, California, for 18 months in 1984-85.

(a)   (b)
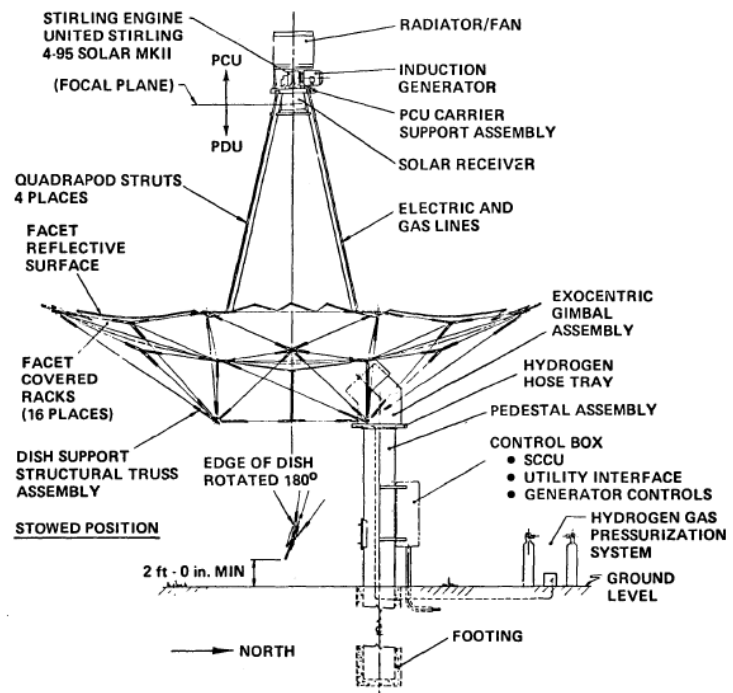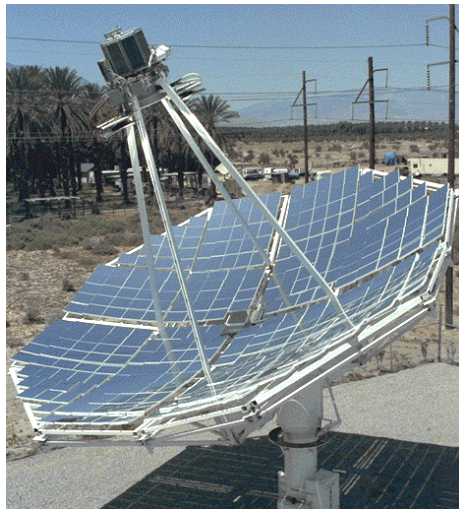
457   *Figure 14. (a) The Vanguard dish and (b) schematic diagram.*

5.13   McDonnell Douglas [29, 32, 75-78]

459   The McDonnell Douglas Astronautics Corp (MDAC) dish reflector consisted of 82 mirror facets to give
460   an aperture area of 87.7 m^2 (Figure 15a). The mirror facets were made of 0.7 mm glass mirrors
461   bonded to a steel backing sheet, which was in-turn bonded to a stamped steel substrate [79, 80].
462   The backing sheet was stamped to a nominal curvature, then adhered to the stamped backing
463   structure while mounted to a mandrel to define final curvature. The facets were a spherical contour,
464   with 5 different radii of curvature to simulate a parabolic continuous surface.

465   The mirrors were mounted on curved truss subassemblies, linked together via a box truss. To
466   minimise torque about the elevation pivot, it is located at the centre of mass between the
467   receiver/PCU and the reflector, which is possible because of the discontinuous nature of the
468   reflective surface. This feature - the cut-out mirror section, or "slotted dish" – has been replicated on
469   many dishes since. For direct heated Stirling engine applications, the flux profile at the receiver
470   needs to be quite uniform, and therefore individual mirror facets required careful canting. The
471   central reflector support subassembly was open on the bottom side, which allowed pedestal
472   mounting without interference. Azimuth tracking was via a pedestal-mounted gear drive, and
473   elevation tracking was via a ball-screw jack. There was a sufficient range of movement to bring the
474   receiver near to the ground for installation and maintenance.

475   The dish was manufactured in six subassemblies, as shown in Figure 15b, each which can be
476   transported by a regular sized truck. The concept provided flexibility to cost-effectively deploy both
477   small and big dish plants. For small installations, entire subassemblies could be shipped from the
478   main factory. For large installations, the main factory would still manufacture components and do
479   some pre-assembly, but several dishes could be shipped on one truck and final assembly would be
480   done on site.

481   Eight dishes were manufactured by MDAC in 1984/85. Originally three were installed at their
482   Huntington Beach test facility in California, and one each at test sites in Barstow (Southern California
483   Edison), Shenandoah (Georgia Power), and Las Vegas (Nevada Power). Since then, the original MDAC
484   dishes have shifted around the US and the world to a variety of solar test facilities, including to the
485   Aisin Seiki Stirling test facility in Japan, the Paul Scherrer Institute in Switzerland, ESKOM [81] and
486   now Stellenbosch University in South Africa.

487   The MDAC dishes were designed for operation with the USAB 25 kW 4-95 Mk II Stirling engine, and
488   successfully operated for long durations. As an example, at least one Stirling dish operated every day
489   from November 1984 until September 1988 [29].

490

491   (a)

492

493   (b)
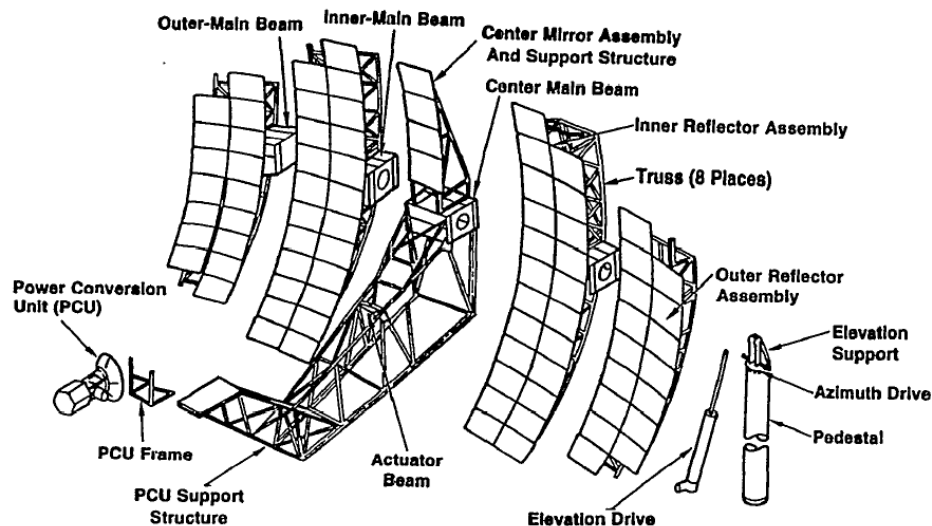
494   *Figure 15. (a) A McDonnell Douglas dish and (b) schematic diagram of dish subassemblies [29].*

5.14   LaJet Energy Company [4, 6, 9, 82, 83]

An example of a 'Fresnel-like' dish was developed by the LaJet Energy Company, a subsidiary of Louisiana Jet Petroleum Company. The open lattice structure was designed with the receiver as a counterbalance to the reflectors. The circular reflectors, each 1.5m diameter, were constructed from polymeric film drawn across an aluminium frame, with curvature imparted by a continuous vacuum. The depth of curvature was adjustable by varying the pressure. LaJet fabricated concentrators using the same type of configuration, but with progressively larger sizes: 19, 38, and 44 m^2.

LaJet was the first company to raise independent finance for a large-scale demonstration project. Solar Plant 1 was a 700-dish installation built at Warner Springs, California, in 1984 using their 44 m^2 concentrator, the LEC-460 dish (Figure 16a). A 4.9 MWe centralised steam power block was connected to 600 dishes that produced saturated steam at approximately 6 MPa, and 100 dishes that were used to superheat to 460°C. The plant was interconnected to the San Diego Gas & Electric Company grid and operated to 1990. Although the plant was a successful demonstration of the concept of centralised steam generation with dishes, some problems were experienced with durability of the polymeric mirrors, and with slow start-up due to excessive thermal inertia in the receivers. The plant was modified to hybrid solar/diesel in partnership with Cummins Power Generation (CPG). A modified version of the LaJet collector (the CPG-460, Figure 16b) was then used by CPG for their 7 kW dish/Stirling development program in the early to mid-1990s [84]. LaJet assembled a 150 m^2 version using the same facets, which was deployed at Sandia in the early 1990s. The dish was fitted with a steam receiver, but suffered from significant structural deflections.


(a)   (b)

Figure 16. (a) LEC-460 dishes at the 700-dish Solar Plant 1 at Warner Springs, California [83]; and (b) the modified version of the LaJet collector, the CPG-460 dish [9].

5.15   Power Kinetics, Inc.[4, 6, 73, 85, 86]

The Power Kinetics, Inc. (PKI) collector, developed in the early 1980s, was an 80 m^2 "square dish" that consisted of many small, flat mirrors mounted on 108 individual curved modular support assemblies (Figure 17a). The assemblies were mounted on a space frame, which was rotated in azimuth on a steel track. The collector was first tested briefly at a concrete products plant in Topeka, Kansas, and then at an installation of 18 dishes at Yanbu, Saudi Arabia, for heat production at a desalination project as part of the SOLERAS project.

524 In 1987 PKI, in collaboration with the Australian National University (ANU), built a modified and
525 much larger version of the square dish concept, a 300 m^2 collector (Figure 17b,c) that was tested at
526 Sandia, Albuquerque, throughout 1988. The reflector comprised 392 curved laminated glass mirror
527 facets (developed by PKI), and had polar tracking, with the central beam aligned with the polar axis,
528 and mirror assemblies extending outwards at 9° on either side. The reflector structure was
529 supported by a tall polar pier (perpendicular to the axis of rotation) and a shorter equatorial pier.
530 The piers were stabilised by tensioned cables from the foundations. The right ascension drive
531 rotated the reflector about the polar axis, and the declination drive provided seasonal adjustment to
532 the ganged mirror assemblies. Although motion was only required to be ±12°, wind feathering,
533 defocusing and mirror position required more than 180° of motion. The receiver was a cavity
534 absorber designed for direct steam generation. Some testing was performed at Sandia with a
535 ground-mounted steam engine based on a modified 4-cylinder Lister diesel engine, similar to those
536 at the White Cliffs project §5.11.The project was a precursor to a planned five dish installation at
537 Molokai, Hawaii, that did not eventuate. Although acknowledged as an uneconomical design [87],
538 the project in part inspired the development of the ANU SG3 Big Dish (§5.21).

(a)

(b)   (c)
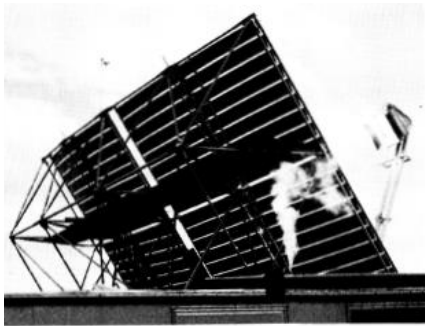
539 *Figure 17. (a) The PKI "square dish" [6]; and (b,c) the 300 m^{2}PKI/Molokai dish at Sandia National*
540 *Laboratories, Albuquerque. Photo: S. Kaneff.*

5.16   DISTAL/Eurodish [7, 8, 84, 88-91]

542 German company schlaich, bergermann und partner (SBP) started development of dish technologies
543 beginning in the early 1980s, initially on the stretched-membrane dish concept. The concept (first
544 described in 1965 [18]) is to use a continuous thin metal membrane stretched across a stiff circular
545 drum, with a second membrane closing off the space behind. A vacuum is then applied to shape and
546 hold the membranes in position. An advantage of this style of reflector is that it can be quickly
547 defocused in case of emergency (e.g. tracking failure).

548 SBPs first project, in conjunction with DLR, was a large 17 m diameter dish, built to operate with the
549 50 kW USAB 4-275 Stirling engines. The first prototype was built at DLR Lampoldshausen, Germany
550 (1983), and then two more (Figure 18) were constructed in Riyadh, Saudi Arabia, as part of the
551 SOLERAS project (1984-88). The reflector was formed with two 0.5 mm thick stainless steel
552 membranes, with 0.7 glass mirror tiles bonded to the front. The 'natural' shape of this dish once the
553 vacuum was applied was neither paraboloidal or spherical. The support structure was a light-weight
554 space frame with elevation tracking via pivots at the outer edges and a circular ring beam, and 6-
555 wheel, central-hub carousel-style azimuth tracking, like the PDC-1 dish (§5.9). Note the base frame
556 and elevation pivots extend in front of the reflector surface, for better balance. At the time, they
557 were first constructed, these dishes were by far the largest solar dishes in the world.

558

559 *Figure 18. The SBP 17 m diameter stretched membrane dishes in Saudi Arabia [92].*

560 The next SBP dish, DISTAL I, was a similar stretched-membrane style but smaller (7.5 m diameter)
561 and with a polar tracking method (Figure 19a). To improve optical performance, it was shown that a
562 parabolic shape could be maintained at the front membrane if the membrane was pre-curved and
563 held under a slight vacuum. The method of curving the 0.23 mm thick stainless steel membrane was
564 to stretch it beyond its elastic limit using a combination of water weights on the front and a vacuum
565 at the back. Again, 0.7 mm glass mirror tiles formed the reflective surface. Six DISTAL 1 dishes
566 prototypes, with were deployed for testing from 1989-92, including three at Plataforma Solar de
567 Almeria (PSA). The DISTAL project tested an 8 kWe version of the Solo V-160 Stirling engine, and
568 accumulated around 30,000 test hours operating three units at Plataforma de Almeria (PSA) in Spain
569 daily from 1993-97.

570 A second generation of the DISTAL concentrator (DISTAL II) was developed for use with the
571 upgraded Solo V-161 Stirling engine (Figure 19b). It was slightly larger (8.5 m diameter) and returned
572 to the carousel-style azimuth-elevation tracking used for the SOLERAS project. Three DISTAL II
573 prototypes starting operating at PSA from 1996-97. As part of this project the Solo Stirling 161 was
574 redeveloped, with increased power and efficiency, and improved manufacturability and
575 maintenance. A first hybrid version with combined solar and gas heat source was developed and in
576 1999 successfully tested at PSA.

(a)	(b)

577

578 *Figure 19. (a) The DISTAL I dishes [92] and (b) the DISTAL II dishes [92], both at PSA.*

579 The EuroDish development was a joint-venture project between several European companies and
580 research institutions, headed by SBP. To simplify shipping the dish, the stretched-membrane
581 reflector from the DISTAL I and II projects was replaced by 12 identical gore-type sandwich panel
582 mirrors, supported at the perimeter by a ring truss (Figure 20). Each panel consisted of two 1 mm
583 reinforced plastic layers with a 20 mm foam core. The panels were stiffened with a radial rib along
584 the centre line, and thin glass mirrors adhered to the panel to form the reflective surface. A similar
585 style tracking system was retained from the DISTAL II dish, but the drive units were redesigned to
586 use standard steel rollers, spur gears and low cost servomotors. In 2001 the first prototypes were
587 installed at PSA, Spain, equipped with the Solo V-161 Stirling engine, and since then EuroDish units
588 have been deployed in many places around the world.
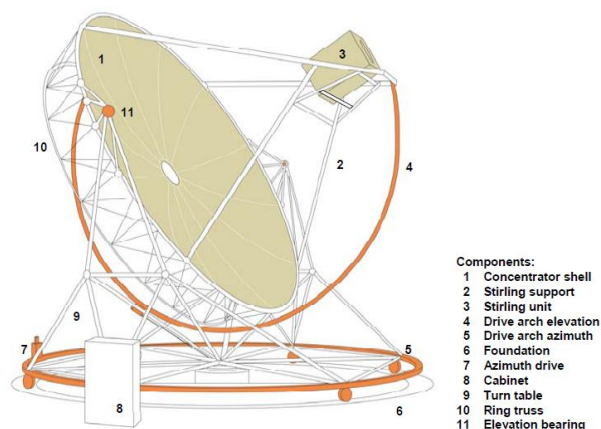
(a)	(b)

589 *Figure 20. (a) The Eurodish [92] and (b) a schematic diagram of the Eurodish [91]*

590 ## 5.17   SKI [18, 93, 94]

591 Solar Kinetics, Inc. (SKI) designed and built a 7-m diameter dish using the stretched membrane
592 technology, and installed it at Sandia, Albuquerque (Figure 21) in 1991. The dish is formed of two
593 membranes. The front membrane is 0.3 mm type 304 stainless steel pre-shaped by plastic
594 deformation to the desired parabolic shape by a combination of non-uniform loading (using with
595 water on one side) and the uniform loading (by a vacuum on the other side). The back membrane is
596 made of a polyester cloth impregnated with PVC, and creates the sealed space for the vacuum. Once

597 the front membrane is shaped, a separate polymer-film reflector is drawn down to the membrane
598 with a slight vacuum. This approach allows the membrane to be replaced in the field. A ring around
599 the membrane is held by a hub-and-spoke arrangement, similar to a bicycle wheel.

(a)   (b)
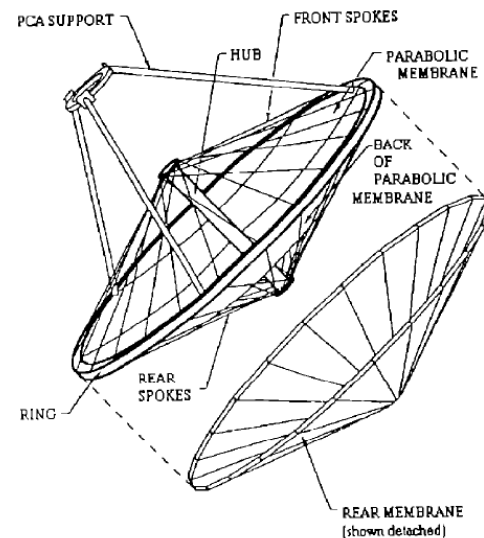
600 *Figure 21. (a) the SKI stretched-membrane dish [18] and (b) schematic diagram showing its*
601 *component [94].*

5.18   Sandia ADDS/WGA dishes [84, 95]

603 A 15.6 m diameter dish was designed by Wilkinson, Goldberg & Associates (WGA) in 1995 for the
604 CPG led Dish-Stirling Joint Venture Program. It was coupled with a heat pipe receiver and an inline 4-
605 cylinder Aisen-Seiki Stirling engine, which operated briefly in 1996 before CPG divested their CSP
606 interests.

607 Subsequently, WGA and Sandia jointly developed two similar but much smaller 8.7 m diameter
608 dishes (Sandia ADDS Mod 1 & 2) for the Advanced Dish Development System (ADDS) program
609 (Figure 22). These were installed at Sandia, Albuquerque, in 1999 and 2000. The dishes were an
610 interesting blend of the MDAC-style slotted dish with balanced elevation drive, and the gore facet /
611 radial back structure concepts of previous full surface reflectors, such as dishes by GE, Acurex and
612 Omnium. The concentric trapezoidal-shaped facets were constructed of thin glass mirrors bonded
613 to a sandwich panel comprising metal face sheets (steel for Mod 1, aluminium for Mod 2) and an
614 aluminium honeycomb core. The use of aluminium sheet metal allowed for a reduction in the
615 number of facets from two rows of 16 facets (32 facets) to one row of 24 facets on Mod 2. The
616 mirrors were bonded to the front face sheet before shaping on a mould. The reflector back support
617 structure was comprised of radial trusses from a centre "hub", with stringers joining the radial arms.
618 The hub is built of thin tubular steel members, so the structure is a kind of space frame, but with
619 radial symmetry and load carried by the radial arms.

620 Sandia National Laboratories bought five solar Solo Stirling 161 engines and further developed and
621 modified them as part of this project, including extensive testing between 2000 and 2002 [95].
622 Improvements included better controls, improved isolation of hot parts, and adaption of the engine
623 to use hydrogen instead of helium. Peak solar-to-electric efficiency was measured over 25%. The
624 dishes and engines were being developed for both grid-connected and remote, unattended

625 operation for off-grid applications such as water pumping. The primary purpose for development
626 was to build a technology demonstration and development platform incorporating the best available
627 technology. The on-grid performance was good, with a geometric concentration ratio of over 3000,
628 which led to the off-grid development. Systems integration, optical improvement, and controls
629 development were featured. The off-grid water-pumping unit is the only off-grid system
630 demonstrated in the modern dish-Stirling era.

631

632 *Figure 22. ADDS dishes with Mod 1 (left) and Mod 2 (right) at Sandia.[95] The Mod-2 system pictured*
633 *is an off-grid water pumping unit.*

634 5.19   SAIC [8, 75, 96, 97]

635 Science Applications International Corporation (SAIC) began development of a dish-Stirling system in
636 1993, having worked on stretched-membrane concentrators for heliostats throughout the latter part
637 of the 1980s. Their first dish prototype, the 12-panel FSM dish was tested in 1995 as part of the USJV
638 program [97], and from 1997 to 1999 SAIC developed and tested four prototype 22 kW "SunDish"
639 dish-Stirling systems (Figure 23a). Two were in Tempe, Arizona, another at the University of Nevada,
640 Las Vegas (UNLV) and a fourth at NREL, Golden, Colorado.

641 These dishes consisted of 16 stretched membrane mirror facets, each 3.2 m diameter, mounted on a
642 truss structure. The mirror facets were stretched membrane reflectors with active focus using a
643 vacuum system. A central blower is used with hoses extending to each facet to induce the vacuum.
644 The facets were mounted in a staggered arrangement to increase porosity and thereby reduce wind
645 loads. The reflector sat atop a pedestal on a gear drive that provided azimuth and elevation tracking.
646 Like the MDAC dish, the elevation axis was located near the balance point between the reflector and
647 receiver.

648 Optical quality of the dish was a key issue for the dish, impacting system efficiency and causing
649 downstream issues at the engine due to flux non-uniformity. For optical performance reasons, and
650 because it was difficult to achieve methods of low-cost manufacture for the stretched membrane
651 facets, SAIC modified the mirror facet design changing from round to flat sandwich-construction
652 hexagonal facets, with small, flat mirror tiles (as shown in Figure 23b). The mirror tiles are supported

653 on a plastic puck that allows the angle of the mirror relative to the flat substrate to be permanently
654 set at any desired value by a robotic assembly system. The new mirror system was demonstrated at
655 the dish at UNLV.

656 The SAIC dishes used the 22 kW STM 120 from STM (now Stirling Power) and logged many
657 thousands of on-sun test hours. The engine used a direct absorption receiver and hydrogen as the
658 working gas [8, 75]. In 2003, a quartz window was included to allow recuperation of exhaust gases
659 and to partly homogenise the light, but it experienced a series of failures [96].

(a)   (b)
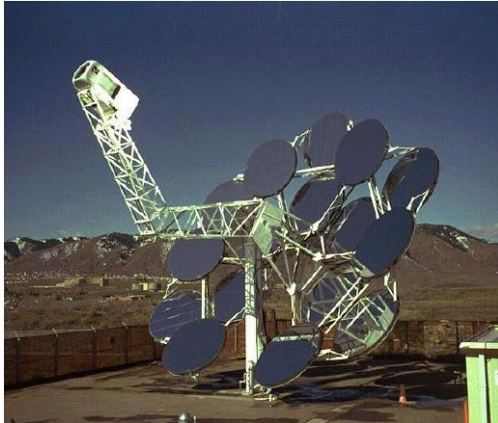
660 *Figure 23. (a) SAIC dish at Salt River Pima-Maricopa Indian community [75], and (b) mirror facet*
661 *production equipment [96].*

5.20   Stirling Energy Systems [77]

663 Stirling Energy Systems (SES) was founded in 1996 to commercialise the MDAC technology, acquiring
664 the rights to the dish and a license to the USAB 4-95 Mk II engine Stirling engine. In the late 1990s
665 Boeing Company (who had acquired MDAC) and Kockums teamed with SES to refurbish the engines
666 and recommended testing of the dish-Stirling systems at the Huntington Beach facility. A study of the
667 mirror panel optics [76] concluded that after 14 years in the field, the mirror panel optics were
668 approximately the same as when manufactured.

669 The first SES-built dish was installed in 2004 at the site of technology partner Sandia National
670 Laboratories in Albuquerque [32]; and dubbed the "Model Power Plant" or MPP. It was an adaption
671 of the MDAC dish, with a modernised control system and new mirror facets based on a sandwich
672 construction of two aluminium face sheets, aluminium honeycomb core, and a thin glass mirror
673 bonded to the front, as developed by Sandia for ADDS (§5.18). This marked the start of 5 years of
674 value engineering, iterating and improving the design to lower cost and improve performance of
675 both the dish and the Stirling engine power conversion unit. Five second-generation MPP dishes
676 were added in 2006, with an emphasis on systems engineering and installation processes. In January
677 2008 a new performance benchmark of 31.25% net solar-to-electric was set on a cold, high DNI day
678 [32] with an MPP dish and a USAB 4-95 Mk-II engine. In 2009, a further four dishes were installed at
679 Sandia with the unveiling of the "SunCatcher™" design. The 25 kWe SunCatcher had a significantly
680 modified reflector structure, with radial trusses and larger, trapezoidal mirror gore facets based on
681 the Sandia ADDS, using a stamped steel mirror construction with a thin glass reflective surface,
682 similar to the original MDAC dishes. The improvements resulted in fewer parts, and a 2.3 tonne mass
683 reduction (~29%). The SunCatcher also featured a driven steel foundation that eliminated concrete
684 and significant field labor. In all, 11 SES dishes were installed at Sandia, including a refurbished

685   MDAC system,6 MPP systems, and 4 SunCatcher systems. In March 2010, the 1.5 MWe Maricopa
686   Solar plant was commissioned at Peoria, Arizona, with 60 SunCatcher dishes.

687   Unfortunately, in September 2011, SES filed for bankruptcy, and the plant was decommissioned. The
688   60 Maricopa dish assets were bought by UK company United Sun Systems International
689   (headquartered in Gothenburg) in 2012 in a joint venture with a Chinese/American company [98]. 30
690   were sent to China, and the rest were held in storage in Phoenix (although some have now been on-
691   sold) [99]. The 11 dishes at Sandia were acquired by Stirling Power of Anne Arbor. The four
692   SunCatcher's were disassembled and moved for later development. The MDAC and four MPP dishes
693   were scrapped, while two MPP dishes remain at Sandia. In 2012 Stirling Power (formerly Stirling
694   Thermal Motors then Stirling Biopower), a subsidiary of Chinese company, Xiangtan Electric
695   Manufacturing Company (XEMC), acquired SES's Stirling engine assets [100].

(a)

(b)

(c)

696   *Figure 24. (a) The SES/Boeing dish [75] (b) the SES SunCatcher at Sandia, Albuquerque, and (c) the*
697   *Maricopa solar plant [Photo: CSPworld.org].*

5.21   SG3 Big Dish

Following on from experience in the White Cliffs (§5.11) and PKI (§5.15) projects, economic studies at the Australian National University (ANU) indicated that the economic viability of dishes might be improved if they were significantly larger [101]. To test this principle and the feasibility of big dishes, the 400 m^2 SG3 "Big Dish" was constructed on site at ANU in 1994, and operated periodically during 1995-2004. The SG3 dish employed a tubular space frame with high-tolerance ball joint connections, forming an accurate paraboloid which allowed the triangular mirror panels to be installed without the need for further adjustment. The mirrors were of a sandwich construction with 2 mm glass, a corrugated steel back face sheet, and a polyurethane foam core expanded in-situ on a curved mould. Azimuth tracking was carousel-style, with a central hub and five two-wheel bogies on a concrete track. The elevation movement employed an elevation support truss that bridged between the base frame and a curved rail at the rear of the reflector. A trolley at the upper pivot of the truss moved along the rail, effectively propping up the dish and moving it up and down. The bogies and trolley were actuated by a hydraulic 'walking ram'. The dish had a cavity-type steam receiver, and although it was designed for central power station applications, the SG3 dish was connected to a small steam engine similar to those used at White Cliffs and synchronised to the grid. A second SG3-style Big Dish prototype was deployed at the Ben Gurion University in Israel soon after SG3 was built.


Figure 25. The SG3 Big Dish at ANU. Photos: Chris Holly

5.22   SG4 Big Dish [38, 102, 103]

In 2005 ANU licenced the Big Dish technology to Canberra-based company Wizard Power, and together developed a second-generation Big Dish, suitable for commercial production. The 489 m^2 SG4 Big Dish was completed in 2009 and has operated periodically since then (Figure 26a,b). SG4 retained the concepts of large size [104] and a similar azimuth-elevation tracking style to SG3, but most other elements were modified. The reflector space frame structure was manufactured in an

inverted orientation on an accurately adjusted assembly jig, which allowed the frame to be welded without little concern about manufacturing tolerances (Figure 26c). The reflective surface was formed by 380 identical 1.17m x 1.17m sandwich panel mirrors, made with thin glass mirrors, two steel face sheets and a medium density fibreboard (MDF) core. Mirror panels were bonded directly to a lattice that formed the front shell of the space frame, without adjustment. Excellent optical accuracy was demonstrated, with peak flux 14,100 suns and an average concentration of 2240 for 95% capture [103]. The base frame was simplified to a triangular geometry, with three wheel blocks on a circular steel rail that also restrained the dish laterally and in uplift. Actuation was by electric drives, in azimuth rotation via a single wheel, and in elevation via a rack and pinion on the elevation truss-rail system. In 2013, Wizard Power was wound up and the rights to the Big Dish IP were acquired by Canberra-based company Sunrise CSP.

Recently, a project to design an optimised superheated direct steam generation tubular cavity receiver for the SG4 dish has been completed. An integrated model for an axisymmetric helical-coil tubular cavity receiver was developed, incorporating optical ray-tracing for incident solar flux, radiosity analysis for thermal emissions, computational fluid dynamics for external convection, and a one-dimensional hydrodynamic model for internal flow-boiling of water [105]. Based on this work, in 2015 a new steam receiver was designed and built for the SG4 dish, and demonstrated thermal efficiency of 97.1% in on-sun testing [38].
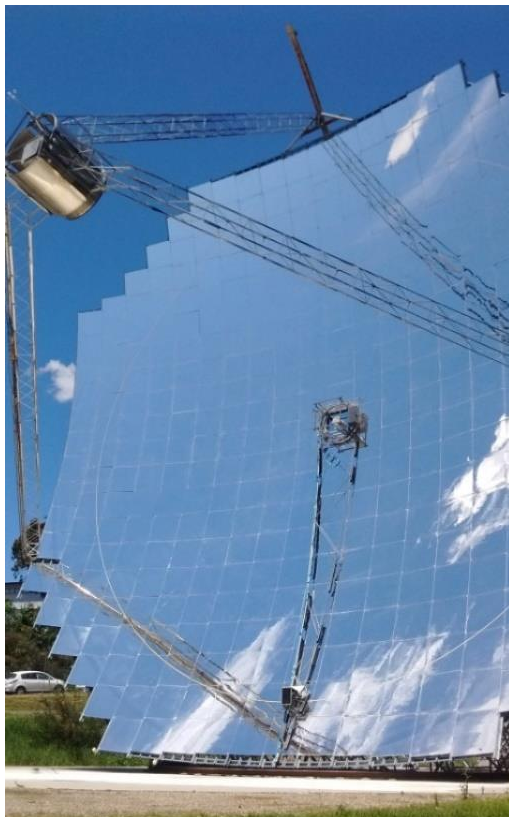
(a)
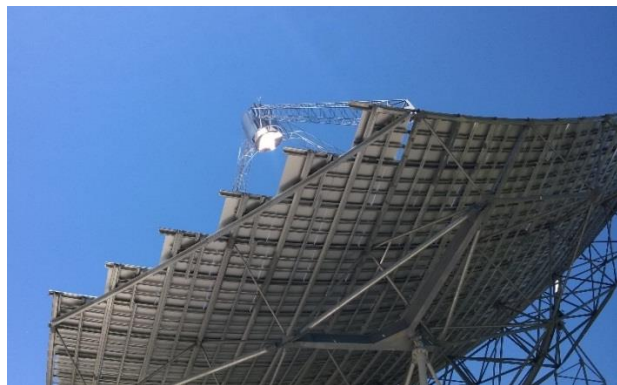
(b)

(c)

Figure 26. (a,b) The SG4 Big Dish at ANU, and (c) lifting the dish reflector frame a jig during construction. Photos: J. Coventry

5.23   Solar Systems [106-108]

Solar Systems began developing dish technologies for concentrating photovoltaic (CPV) applications from 1990. From 1998 to 2004 Solar Systems used the White Cliffs dish installation §5.11 as a test bed, and in the early 2000s, developed the SS20 dish (later renamed CS500), initially with two prototypes at Fosterville, Victoria (Figure 27). The reflector structure was a radial truss arrangement, overlayed with a rectangular mesh for mounting the mirrors. Each dish has 112 identical 1.1m x 1.1m mirror facets, and total aperture 130 m^2. The original panels were made by injecting high density foam into a mould, then bonding the 2 mm mirror glass into the shape under pressure [109]. For later dishes, Solar Systems developed a novel way of shaping the foam by bending a foam sheet on one axis, and cutting a curve with a wire cutter on the other axis [110]. Once the bend is released, the resulting curve is spherical. Tracking was via a pedestal mounted azimuth-elevation configuration. Solar Systems employed a reflective flux homogeniser in front of the CPV module, in combination with a careful procedure for adjusting the alignment of each mirror, to achieve a near uniform concentration of 500 suns at the receiver.

Solar Systems switched from silicon to multijunction III-V modules in 2006, and in on-sun testing at Hermannsburg, recorded peak solar-to-electrical (DC) of 24.7% excluding parasitic energy for the cooling pump, tracking motors and control system [108]. Cell efficiency continued to improve, and by 2013 Solar Systems claimed solar-to-electrical (AC) efficiency of approximately 30% for a complete power plant installation [46].

In total, Solar Systems installed around 130 dishes, including 45 at five outback Queensland and Northern Territory sites, 40 in Mildura in 2013 as the first stage of a planned 2000 dish facility, and 28 at Nofa resort, Saudi Arabia, in 2014. After financial difficulties, Solar Systems was bought by Silex Systems in early 2010, however operations eventually were ceased in July 2015.
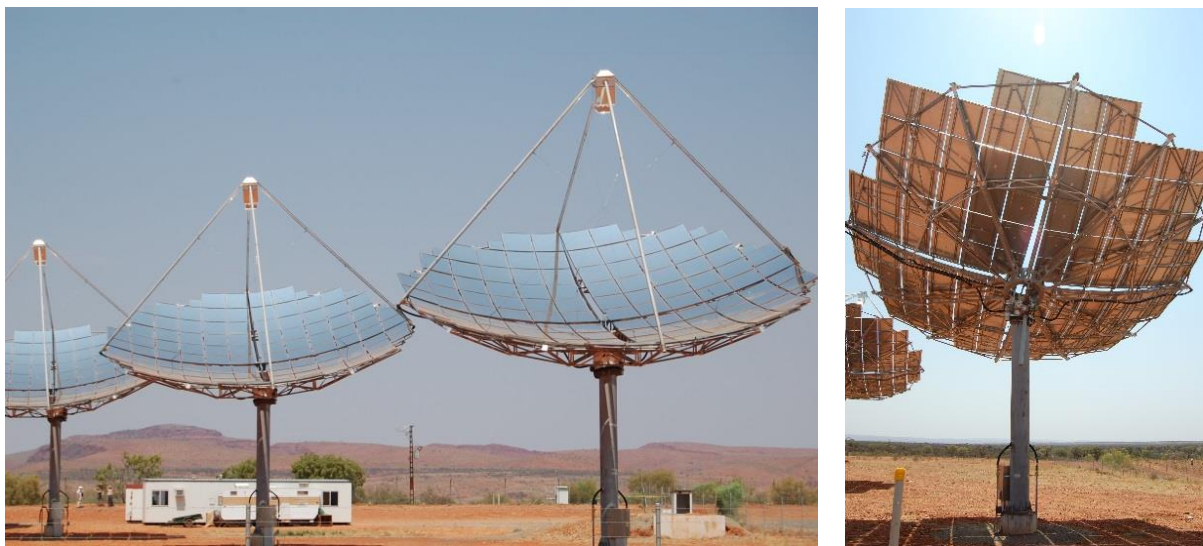

Figure 27.   Solar Systems CS500 dishes at Umuwa, central Australia. Photos: Joe Coventry

5.24   ARUN [111]

The ARUN^{TM} dishes are Fresnel-type, multi-faceted dishes developed by Clique Solar, in partnership with IIT-Bombay, primarily for supply of process heat. Initial prototyping began in 1998 and utilised polar-equatorial style tracking similar to the PKI dish §5.15. More recent models are pedestal mounted, azimuth-elevation style, with the elevation pivot located behind the reflector and

772 employing a counterweight for balance. The company presently offers three different models, the
773 ARUN 30, 100 and 160 (with aperture area 34 m², 104 m², 169 m² respectively, Figure 28). The dishes
774 are designed for various heat transfer fluids including steam, hot oil, hot water and hot air at
775 temperatures up to 350°C and pressures up to 25 bar. Commissioned in 2006, the first industrial
776 project was a single dish providing pressurised hot water at 180°C to at a dairy in Latur, India. Since
777 then dishes have been installed for a variety of process heat applications in India.

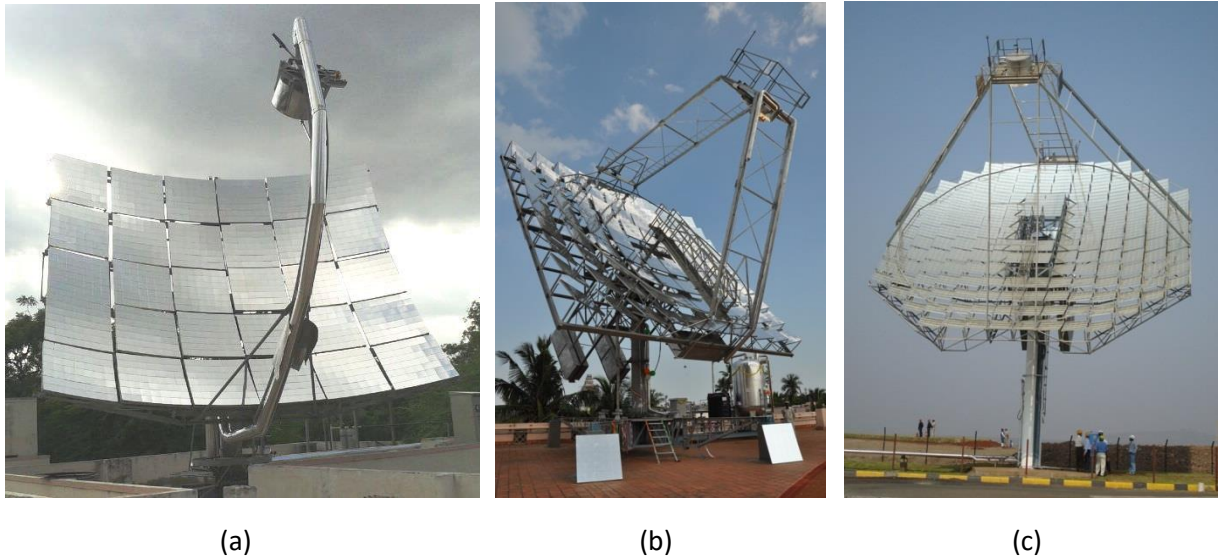| (a) | (b) | (c) |

778 Figure 28.Fresnel-type dishes from Clique Solar (a) ARUN 30, (b) ARUN 100, and (c) ARUN 160 [111]

5.25 HelioFocus [92, 112, 113]

780 The HelioFocus 500 m² faceted dish concentrator concept was developed in partnership with SBP
781 from 2008. The first dish prototype was installed in Dimona, Israel, in 2012 (Figure 29a). The
782 reflector employed 219 mirror facets, each 1.5 m x 1.5 m, arranged in a Fresnel-like array. The steel
783 reflector structure had a stiff torque box at the base, with seven 18 m long cantilever arms extending
784 to the top of the dish, linked transversely by circular purlins. The mirrors were bent glass, supported
785 at five points and mounted on the purlins. Tracking was carousel-style with a central hub for lateral
786 guidance, a steel base ballasted with concrete to prevent overturning, and four wheel bogies
787 mounted on a circular crane rail. Both azimuth and elevation axis were driven by hydraulics, with a
788 2-cylinder pilgrim step drive on azimuth rotation, a little similar to the SG3 Big Dish walking ram
789 system, but allowing continuous motion. A second prototype, the 'Orion' dish, was designed with
790 some modifications, and installed at the 8-dish Orion plant near Wuhai, Inner Mongolia in 2013
791 (Figure 29b). The Wuhai installation had an air receiver, and reticulated hot air for centralised
792 boosting of a steam cycle, but the plant was never commissioned. HelioFocus was formally shut
793 down in early 2017 [114].
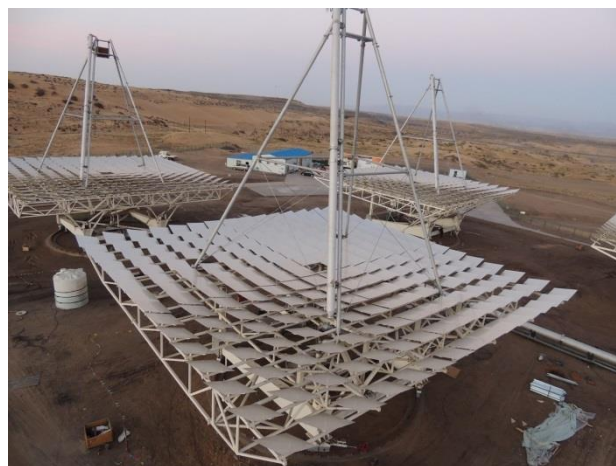
<div style="text-align:center">(a)</div> <div style="text-align:center">(b)</div>

Figure 29. (a)The first HelioFocus dish prototype in Dimona, Israel and (b) the pilot plant near Wuhai, in Inner Mongolia. Photos: SPB [92].

5.26 Southwest Solar [115-117]

The 320 m^2 SST Big Dish was developed by Southwest Solar Technologies Inc. and installed in Phoenix, Arizona, in 2011 (Figure 30a). The dish was designed for use with an 80 kWe Brayton turbine from Brayton Energy LLC. The dish concept builds upon previous designs (e.g. SES SunCatcher) with a cut-out reflector, radial truss structure, and balanced pedestal mounting. Subsequently Southwest Solar, has developed a new dish design, the 54 m^2 SST Dish 600, initially targeting CPV applications (Figure 30b,c). The reflector consists of 12 mirror composite mirror panels, and each panel has 18 glass tiles. For prototyping a customised curvature is CNC machined into a rough-shaped polyurethane core behind each tile to tune the flux profile, and achieve the uniformity necessary for a CPV receiver. A moulding process is planned for the production version. Initial prototypes will be deployed at King Saud University in Saudi Arabia. The tiles can be curved to a parabolic shape for point-focus thermal applications. Smaller mirror facets of this type were recently installed at a solar furnace at UNSW, Australia [118].

<div style="text-align:center">(b)</div>

(a)

(c)

Figure 30. (a) The 320 m² SST Big Dish installed in Phoenix, Arizona,[116] and (b,c) the 54 m² SST Dish 600 [116, 117].

5.27   Infinia PowerDish [9, 92, 119-122]

Infinia Corporation was founded in 1985 and has developed Stirling engines (and cryogenic coolers) for many applications, including space exploration, cooling supercomputers, and residential combined heat and power. In 1986-88 Infinia designed a 25kWe solar-electric Stirling power system for NASA and DOE for a solar dish plant, and in 1991-94 developed a hybrid solar/natural gas power system for NREL. In 2001, a 1kWe Infinia Stirling generator was operating at the NREL solar furnace.

In 2004 effort began to develop and commercialise a dish-Stirling system, known as the PowerDish. The dish was designed together with SBP, with assistance from Sandia. Four generations of PowerDish designs are described by Prinsloo and Dobson [119]. The 4.7 m diameter PowerDish II and III used a reflector with circular hub and radial beam mirror supports, with a cut out reflector, and pedestal mounted elevation axis balancing the dish and the PCU (Figure 31a,b). The mirrors were thin glass bonded to 6 glass fibre reinforced plastic petal-shaped facets. Infinia commissioned its first commercial installation of 34 PowerDish II units in Yuma, Arizona, in August 2010, and subsequently over 100 PowerDish II and III units were deployed around the world, including 30 units in Villarrobledo, Spain, in partnership with Renovalia.

The PowerDish IV was developed and first deployed at the Tooele Army Depot project, which was planned to be a 430-dish installation (Figure 31c,d). It had a quite different dish design, with the mirror cut-out removed, and instead a counterweight used to balance the reflector and 3.5 kWe PCU. The dish frame structure used a lightweight radial steel frame stabilised by tension cables attached to the counterweight support, at both the front and rear of the mirrors. Curved slumped glass mirrors are mounted at three points to the circumferential framing. The elevation axis mount is laterally offset from the azimuth axis mount to allow the necessary range of movement (Figure 31e).

In parallel with the dish development, Infinia began to concentrate on commercialising a 3 kWe Stirling engine designed for the PowerDish. As the engine was hermetically sealed, Infinia claimed no maintenance was necessary over the entire 25-year life span.

By August 2013 the first 180 PowerDish IVs were on sun at Tooele Army Depot, but unfortunately in September 2013 Infinia filed for bankruptcy. The assets were later acquired by Qnergy.

(a)

(b)

(c)   (d)   (e)

Figure 31. Infinia dishes: (a) PowerDish II [92]; (b) PowerDish III [92]; (c,d) PowerDish IV [120]; and (e) the laterally offset elevation drive of the PowerDish IV [120].

5.28   ZED Solar [123, 124]

The Solar Invictus dish from ZED Solar (designed by AEDesign) is a 9 m diameter pedestal mounted dish (Figure 32). The mirrors are petal-shaped, with two rings of 15 mirrors, interconnected by radial trusses mounted on a cylindrical hub. The entire steel reflector structure is located in front of the mirrors. The overall mass of supporting structure is minimised by making use of the structural properties of the mirrors. Otherwise the design is a conventional azimuth-elevation tracking, pedestal mounted design, with cut-out reflector and balanced reflector-PCU elevation axis mounting. Zed Solar constructed its first two prototype dishes in Lahore, Pakistan in 2010 and 2012, supplied a prototype dish to Cleanergy in Åmål, Sweden, in 2012, 10 dishes to the Cleanergy pilot plant in Dubai in 2014 and a prototype with a steam receiver designed for enhanced oil recovery in Abdali, Kuwait, in 2016.

(a)

(b)

(c)
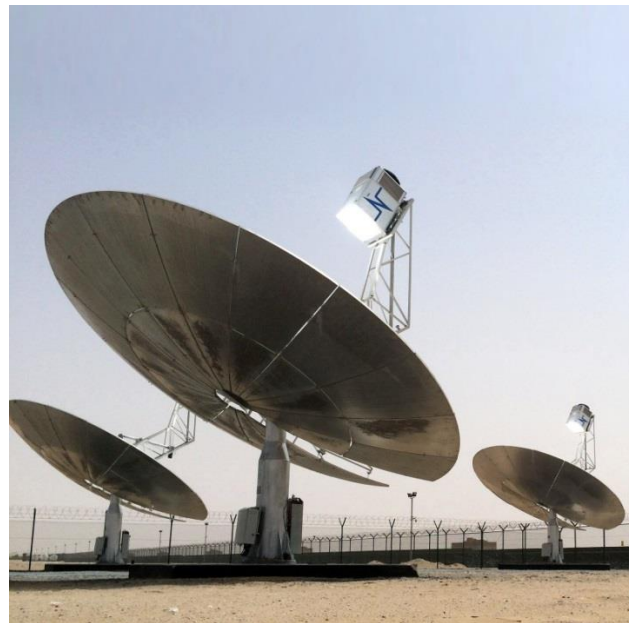
Figure 32. (a,b) ZED Solar dishes (with Cleanergy Stirling engines) at the Dubai plant [125], and (c) a ZED Solar dish with a steam receiver [126].

5.29   Ripasso [33, 127, 128]

Ripasso was formed in 2008 primarily to develop and commercialise a Stirling engine licensed from Kockums. In 2012, they set the current solar-to-electric efficiency record, 32%, on a 28°C day, with a Stirling engine licenced from Kockums, and a dual-reflector dish located near Upington in South Africa (Figure 33a). The dish tracking system is from Spanish company, Titan Tracker. More recently Ripasso has developed their own complete dish prototype at the same test site (Figure 33b). The design of the reflector and light-weight truss receiver supports are similar for both dishes. The mirror facets are made up of a glass mirror bonded to a reinforced plastic composite, made by resin transfer moulding (RTM). The Titan Tracker is a carousel-style tracker, with central hub. The new dish has a single reflector, with a four-wheel carousel-style movement in azimuth rotation, and a large cradle-like structure for elevation rotation. The 'cradle' is a space frame spanning between two semi-circular ring beams, passing over rollers mounted directly above the azimuth rotation wheels. The cradle has a counterweight at the rear of the dish for balance.

(a)   (b)

Figure 33. Ripasso test site at Upington, South Africa, with (a) dual reflector [129] and (b) single reflector prototypes [130].

5.30   Great Ocean Energy [131-133]

Great Ocean Energy (GOE) has constructed a series of dish installations. In July 2012, a 100 kW dish Stirling demonstration plant was built at Ordos in Inner Mongolia (Figure 34a). The plant comprises 10 dishes each with a 10kWe Stirling system from Cleanergy. The dish design is similar the SES Suncatcher 25 kWe design, but is smaller with a 9.2 m diameter. In 2013, GOE supplied another of these dishes to a Cleanergy for a prototype installation in Seville, Spain. In 2015, GOE installed two 25kW dish-Stirling prototypes in Zhang Jiagang, in Jiangsu Province (Figure 34b). One appears to have a reflector modelled on the ZED Energy Solar Invictus, and the other appears to be a carousel-style tracking style, similar to the EuroDish. Great Ocean Energy has developed a 25 kW Stirling engine for its dish. Per the Chinese version of the company website, in December 2015 it had capacity to produce 10,000 Stirling engines per year and plans to increase production to 100,000 per year.

(a)   (b)

Figure 34. (a) GOE dishes in Ordos, Inner Mongolia, with Cleanergy Stirling engine receivers [132], and (b) GOE dish prototypes in Zhang Jiagang, in Jiangsu Province [131].

5.31   Cleanergy [132]

Cleanergy was established in 2008 as a developer of Stirling engines. As discussed above its initial testing of the Cleanergy Stirling engine employed dishes procured from others, but in early 2016

885 Cleanergy deployed its own dish design at its demo park in Dubai (Figure 35). The dish is of a similar
886 design to the other ZED Solar / AEDesign dishes at the Dubai facility, but a little larger to match
887 increases in input thermal power requirements of the Cleanergy's Sunbox Stirling engine.

888 Cleanergy's engine development is based on the Solo V-161 engine, which it acquired from Stirling
889 Systems AG and EBM of Switzerland in 2008 (who themselves had bought the technology from Solo
890 Stirling GmbH in 2007). The engine has since been developed further and new models released
891 (C11S, Sunbox) [132]. The 11kW C11S unit had modernised electronics plus other tweaks and
892 accumulated 20,000 operational hours over the first 12 months of testing at a 10 dish installation
893 installed in Dubai in 2015 [132]. Further improvements are ongoing, including improvement of the
894 working gas channel to improve the gas cooling [134].

895

896 *Figure 35. The Cleanergy dish in Dubai [132].*

5.32   Thermax [135]

898 The 16 m^2 Thermax SolPac™ D160 (Figure 36) is a so-called Scheffler dish [22], where the focus is
899 fixed and the reflector is a segment of a paraboloid with daily east-west tracking, and slow seasonal
900 adjustment of declination, as introduced earlier (§3). The Thermax reflector geometry is set based
901 solar declination = 0° (at the equinox), and because the dish and receiver have fixed heights, the
902 reflector would require different segments of a paraboloid to achieve an ideal focus as solar
903 declination changes throughout the year. This is not practical, and therefore optical quality is
904 compromised. However, for the 150°C process heat applications for which Thermax market this dish,
905 the solar concentration is sufficient based on the fixed shape reflector.

906

907 *Figure 36. The Thermax SolPac™ D160 dishes [135].*

5.33   BioStirling-4SKA [136-138]

BioStirling is a large European consortium developing a dish-Stirling technology aimed to provide power to the Square Kilometre Array (SKA) project in Portugal. The dish design and fabrication is led by Spanish company, Gonvarri Steel Services. The dish is designed to power a hybrid solar/gas Stirling engine, by Cleanergy. Mirrors are by ToughTrough, which develops sandwich panels with steel face sheets and polyurethane core. The steel structure (Figure 37) for the first prototype was deployed in September 2016.

Figure 37. The steel structure for the BioStirling dish, without mirrors installed [136].

6 EVOLUTION OF PARABOLIC DISH DESIGNS

6.1   Size

A contractual requirement by JPL in the development of the TBC dishes (§5.6) was "adapting an existing, proven antenna structure" [12]. This risk minimising approach led to development of an 11 m diameter dish, which also happened to match the input requirements of a commercially available Stirling engine (the 25kW USAB 4-95). Once the engine R&D programs were established, for practical and cost-effectiveness reasons, dish size was effectively 'locked in' for a period of first 5-10 years of the US dish program. Stirling engine availability has continued to dictate dish size since, although other smaller engines (8kW V160, 3kW Infinia) have been introduced. Indeed, as the Stirling engines were improved and become more efficient, dish sizes were incrementally increased, rather than engine sizes decreased. Dishes intended for other applications (steam, process heat) had less constraints on size, which lead both to both bigger (e.g. ANU §5.21) and smaller sizes (e.g. Shenandoah §5.4) than were being contemporaneously developed for dish-Stirling applications.

Size has been a topic of great debate for heliostats [139-141], but less so for dishes probably because of the constraints imposed by Stirling engines. If dish size could be chosen freely, what would be optimal? Lovegrove et al. [104] analysed cost dependency on size, by weighting cost dependency on radius (r) of the dish to the power of 0,1,2 and 3 (*i.e. 1, r, r^2, r^3*). Using a cost breakdown from the ANU Big Dish (with its steam receiver) as a case study, the analysis suggested large dishes may be more economical, with a broad optimum size between about 7 - 20 m radius. Dish-Stirling systems have higher receiver-to-concentrator cost ratio, which would further increase the optimal size range by this method. However, there are perhaps additional drivers relating to volume manufacturing, shipping and assembly (as discussed for heliostats by Coventry and Pye [140]) which favour smaller size. It is well known volume manufacturing of engine components is

940 critical to low cost vehicles, and the same is likely to be true for Stirling engines, favouring more
941 numerous, smaller engines and therefore dishes (Figure 38).

942 *Figure 38. Infinia Stirling engines in production [142].*

6.2 Tracking style

944 Both pedestal and carousel style tracking were tried from the early days of the various dish
945 programs (e.g. THEK 1 §5.2, PDC-1 §5.9 vs. PDC-2 §5.10) and both styles have been continued to be
946 pursued in recent commercialisation efforts. On balance, more progress towards commercial
947 success has been seen with dishes employing pedestal style tracking (SES §5.20, Infinia §5.27),
948 perhaps because of better opportunity to reduce drive and foundation costs, as discussed below in
949 §6.5.

950 An interesting design conundrum for dishes intended for heavy receivers such as Stirling or Brayton
951 engines, is how to design a balanced, lightweight structure with centre of mass near the elevation
952 pivot, and yet also achieve a suitably uniform flux profile. There have been many variations of the
953 MacDonnell Douglass style dish (§5.13), with a slotted reflector to allow pedestal mounting at the
954 centre of mass. To achieve good PCU efficiency and service life, the mirrors must be carefully aligned
955 to compensate for the gap in the reflector. Mirror alignment can be a time-consuming task;
956 however, for most facetted designs it is necessary regardless of whether the dish has a continuous
957 surface or is slotted, and therefore the addition of a slot does not add additional cost with regards to
958 alignment. There are two main alternative designs that have been demonstrated that are balanced,
959 and not require a slot in the reflector surface. The reflector may be pivoted about its outer edges,
960 for example PDC-1 §5.9 and DISTAL/Eurodish §5.16 , or the pedestal mounting may be located
961 behind the reflector but with addition of a counterweight, for example the Infinia PowerDish IV
962 §5.27 and ARUN §5.24.

963 Pedestal mounting is near ubiquitous for state-of-the-art heliostats, and is common for dish designs
964 with lightweight receivers, particularly CPV receivers. However, in these cases the pedestal and
965 elevation axis is usually located behind the reflector, as balancing mass is not as critical to
966 practical/economic design of the actuation or support structure. Examples are Solar Systems CS500
967 (§5.23) and Southwest Solar SST Dish 600 (§5.26).

968 Other tracking styles have also been demonstrated, (e.g. polar and declination axes at Shenandoah
969 §5.4) but are little seen in recent designs.

6.3   Structure

The large reflector surfaces of dishes need to be supported by some form of structure. The design of the dish reflector structure very much depends on the style of tracking chosen. Dishes that utilise the central pedestal style of tracking need to bring the loads to the centre, which is naturally accomplished with a radial structure (e.g. Solar Systems §5.23, SES §5.20, Infinia §5.27, ZED Solar §5.28, Ripasso §5.29, Sandia/ADDS §5.18). Dishes that are supported at, or near, the perimeter are better suited to a ring truss (e.g. EuroDish §5.16) or space-frame (e.g. PDC-1 §5.9, ANU Big dishes §5.21 & §5.22). A well-designed space frame is light, structurally efficient and makes optimum use of material [143], and therefore space frames have also been used for a number of pedestal mounted dishes, despite additional complexity in fabrication compared to radial trusses (e.g. Vanguard §5.12, LaJet §5.14). For the PDC-2 dish §5.10, a hybrid ring truss – space frame arrangement was used. The ring truss was located between the inner and outer rows of gore facets, and supported the facets with lightweight outriggers. The ring truss was connected back to the pedestal via a space frame.

A key exception to the styles described above is the MDAC dish §5.13, which used a Cartesian structure, more akin to state-of-the-art heliostat designs (e.g. Abengoa Sanlúcar 120 [144], Sener heliostat [145]) than most other dishes. This was done to fit the finished structures onto trucks for delivery of pre-built assemblies.

As noted by Jaffe [5] the distinction between faceted and Fresnel reflectors is not sharp, and with properly oriented facets, there is no need to maintain an overall parabolic shape. The facets can be placed on a support frame of virtually any shape if there are advantages to do so (design, aerodynamics, cost) but at the cost of blockage by adjacent facets, unless gaps are left. Gaps between mirrors reduce the effective aperture of the concentrator. Dishes of this style include PKI §5.15, ARUN §5.24 and HelioFocus §5.25 dishes, as well as some of the multi-faceted stretched-membrane concentrators (e.g. SAIC §5.19). As well as the optical compromises of this style of dish, there are structural disadvantages because there is no option to make use of mirror facet structural properties.

The concept of a front web structure was first demonstrated by General Electric for the PDC-1 §5.9, although in tandem with a space frame at the rear. However more recently, the use of a front web structure without a rear space frame was introduced by ZED Solar §5.28 and has seen application by other companies (Great Ocean Energy §5.30, Cleanergy §5.31). This approach may more directly couple the dish structure to the drive at the centre of gravity, with potential savings in steel mass.

6.4   Mirror panels

Any discussion about what constitutes a 'good' mirror panel should consider both performance and cost aspects. Cost includes not just the cost of the mirror facet itself, but the impact on the cost of the dish as a whole.

Andraka [80] discussed the trade-offs between cost and performance of reflectors used for dish concentrators, and showed that, for high temperature Stirling dish systems, good optical performance is critical to achieving low levelised cost of energy. As an example, it was shown that a dish with 3.0 mrad slope error had annual performance 21.8% lower than the 0.8 mrad baseline.

It is important to understand the error source, and distinguish between random and systematic errors. Error sources that affect receiver aperture size have a strong impact on performance due to thermal losses. Error sources that increase peak flux will impact the service life of a receiver, and this is true for all receiver types although particularly important for receivers with poorer internal heat

transfer (e.g. when there is a vapour phase in the HTF). Andraka observed that systematic errors due to sources such as facet shape, alignment, structural deflections, and tracking errors, can typically be minimised by careful design, manufacturing quality control, quality alignment tools and closed-loop tracking control. In particular, on high flux high performance systems, optical alignment is critical and needs to be better than 0.25 mrad RMS on a typical gore-facet dish [146]. The impact of alignment is partially on performance, but greatly impacts service life due to peak fluxes.

If good alignment is achieved, and the structure is sufficiently stiff, this leaves mirror facet RMS slope error and shape error as the most critical variable for good performance. At a single point on the mirror, slope error is defined as the difference between the actual measured surface normal vector and the ideal surface normal. To describe the accuracy of a surface, the root mean squared (RMS) value of multiple measurements is commonly used[3]. Andraka [80] reviewed reported facet slope errors, and data from this review is reproduced in Table 2 along with some additional examples.

Table 2. Slope errors reported for a selection of dish concentrators. Slope error values from Andraka [80] except where additional reference is given.

Dish	Section, Ref.	Facet construction	Slope error (mrad)
Shenandoah	§5.4, [56]	Stamped aluminium, reflective film	5.5
Sandia TBC	§5.6	Foam glass	0.5
Advanco / Vanguard	§5.12	Foam glass	0.5
Cummins / LaJet	§5.14	Mylar stretched membrane	1.5–2.5
SAIC	§5.19	Stainless stretched membrane, facets	2.5–3.5
SKI	§5.17	Stainless stretched membrane, whole dish	1.2–3.5
MDAC	§5.13	Stamped steel with thin glass	0.6–1.5
WGA / ADDS	§5.18	Sandwich aluminium facets, thin glass	0.8–1.4
DISTAL II	§5.16, [148] [149]	Stainless stretched membrane, whole dish	2.6-3.2
Sandia TBC (replacement mirrors)	§5.6	Sandwich construction	0.4–1.0
SES / Paneltec	§5.20	Sandwich construction, thin glass	0.8

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[3] More correctly, the mode of the measured angular error distribution should be determined, per the method recommended by Johnston [147] Johnston G. On the Analysis of Surface Error Distributions on Concentrated Solar Collectors. Journal of Solar Energy Engineering 1995;117:294-296, but RMS is a simpler proxy for this value.

SG4 Big Dish	§5.22	Sandwich construction, thin glass	1.3
Flabeg trough mirrors	[150]	Slumped glass	1.7
Stellio heliostat mirrors	[151]	Flat glass, curved on support frame	0.9–1.2
Sener heliostat mirrors	[145]	3 mm glass, on stamped backing	0.94

1027 Although some of the early dishes had highly accurate but expensive facets (e.g. TBC §5.6, Vanguard
1028 §5.12), low-cost fabrication methods were pursued from the earliest days of dish development. For
1029 example, General Electric's Shenandoah dish had reflective film adhered to die-stamped aluminium
1030 mirrors with rear ribs (Figure 39). Although optical accuracy targets for this dish were not high,
1031 stamping is potentially very cost effective for high volume manufacturing (despite the high cost of
1032 initial development due to the dies), and promising optical accuracy has been demonstrated.
1033 Stamped mirror panels were employed for the MDAC dish §5.13, and measurements by Sandia
1034 indicate <1 mrad slope error, with some better than 0.8 mrad. Stamped constructions have also
1035 been used extensively for heliostat mirrors, such as Gemasolar [145] with slope error < 1 mrad
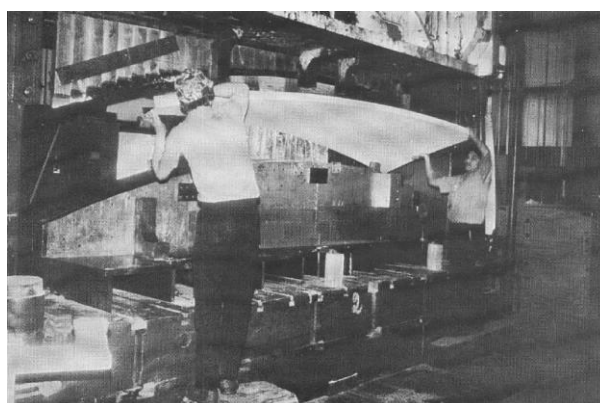1036 reported.

1037

1038 *Figure 39. Die stamping the mirror panels for the Shenandoah dishes [56]*

1039 The highest optical performance has been for sandwich panels, including for dishes such as Sandia
1040 ADDS §5.18, SES §5.20 and the SG4 Big Dish§5.22, with RMS slope error spanning a range of 0.8–1.4
1041 mrad. Current commercial suppliers of sandwich mirror panels include ToughTrough and RioGlass
1042 Solar. Toughtrough has developed a steel and glass faced, polyurethane cored sandwich panel,
1043 which has been used for heliostats [152, 153] and will be used for the BioSolar-4SKA dish project
1044 (§5.33). The specific weight of the mirrors is less than 10 kg/m^2 and the foam core is designed with
1045 inhomogeneous density, i.e. the foam density is locally tuned according to structural requirements
1046 [154].

1047 As introduced earlier (§3), the development of stretched-membrane concentrators was motivated
1048 by the possibility of achieving very low cost. However, although there is a wide range of reported
1049 slope error values, it is apparent in Table 2 that the optical performance of this type of concentrator
1050 is not as good as stamped or sandwich constructions. The stretched membrane facet accuracy was
1051 limited by both edge effects, as well as anisotropic behaviour as the membrane was stretched.

1052 Slumped glass mirrors, which are almost standard for parabolic troughs, are rarely used for dishes.
1053 Thermally slumped mirrors are heavier, require a more rigid support structure, and historically did

1054   not have good enough optical accuracy for dishes. However, optical quality has gradually improved,
1055   and one of the major manufacturers Flabeg FE, now claims slope error < 1.7 mrad for trough
1056   applications [150].

1057   Little information has been published about the optical performance of panels made of glass bonded
1058   to reinforced plastic substrates, such as those used for the Eurodish, Ripasso, and earlier Infinia
1059   dishes.

1060   Finally, it is noted that mirrors for some state-of-the-art heliostats use flat glass, shaped only by the
1061   support structure (e.g. Stellio [151] and BrightSource). Flat mirrors are supplied with flatness
1062   typically <0.3 mrad [150], and once shaped can achieve very good RMS slope error around 0.9 mrad,
1063   or 1.2 mrad across a day in operation in the field [151]. This design is challenging for dishes, which
1064   have significantly smaller radius of curvature compared to most heliostat fields.

1065   Reliable public cost data from manufacturers is not readily available for any of the mirror
1066   constructions. The cost of a glass-steel-polyurethane-steel sandwich mirror panel was estimated by
1067   DLR in 2013 at about 40 USD/m^2, comprising steel (12 USD/m^2), the mirror (12 USD/m^2) and the core
1068   material (15 USD/m^2) [154]. Stamped panels might be expected to be lowest cost in a high-volume
1069   scenario, based on the industrialised nature of the stamping process and the requirement for less
1070   material (i.e. no core material). However, sandwich panels have an optical performance advantage
1071   primarily due to continuous support of the reflective surface across the areal extent of the facet, and
1072   they can be designed to be strong and very rigid. If a dish is designed with sandwich panels well
1073   integrated to minimise supporting structure, they may be a cost-effective alternative to stamped
1074   panels.

6.5   Cost reduction opportunities

1076   In a 1985 summary of 10 years of well-funded dish development under the US dish program, Panda
1077   et al. [6] commented that "indications are that bringing concentrator costs down to target levels will
1078   not be easy. Concentrators must be designed from the start for low-cost mass production, using
1079   good production engineering and cost-effective technology". Some specific comments were made
1080   about dish designs as follows:

1081 •   Single-post mounts tend to be lighter and cheaper than mounts using tracks or multiple
1082   pedestals
1083 •   Initial design should minimise field assembly and alignment, to minimise field labour costs (in
1084   the US context)
1085 •   Inexpensive foundations are needed (e.g. pier foundations often cheaper than concrete pads)

1086   These comments are consistent with lessons learnt from more recent dish developments, and the
1087   personal experience of the authors. The drive systems, especially azimuth, are a substantial cost. The
1088   cost is driven by the need to support a large overturning moment, while maintaining accuracy in
1089   tracking. The carousel-style drive approach easily supports the overturning moment, but generally
1090   requires more extensive site preparation and foundations, driving in-field labour costs. Several CSP
1091   developers (SES for dishes [155], BrightSource for heliostats [156]) have eliminated concrete pier
1092   foundations, and utilized driven or vibrated steel pedestal/foundation drive supports. This
1093   significantly swings the cost drivers in favour of a pedestal type support tower, despite the higher
1094   gearbox and bearing costs.

1095   Modularity has long been mentioned as an advantage for dishes over larger scales CSP systems (e.g.
1096   Acurex [157]). However, more recently dish systems have been proposed in very large fields to

1097 reduce cost by productionisation of the installation and assembly (e.g. SES, Infinia). The design of the
1098 dish needs to reflect the deployment model, as different competing features are needed for small
1099 and large installations. In all cases, the cost is minimised by minimising in-field labour. However, on-
1100 site (centralised) assembly and optical alignment, while more expensive than factory assembly, can
1101 offset the significant cost of shipping (partially) pre-assembled systems, especially for large-field
1102 installations.

1103 Sandia, working with SES, found that significant savings in structure could be obtained by designing a
1104 dish to optical specifications rather than structural deflection specifications. A single number for
1105 maximum deflection under gravity loads and wind loads leads to over-design of portions of the
1106 structure. Instead, coupled optical and structural analysis can lead to better optimisation of the
1107 structure cost. Utilisation of structural (sandwich or otherwise) facets to carry some loads, either
1108 through cantilever designs or by joining the facets rigidly together has the potential to further
1109 reduce structure costs.

7 STORAGE AND HYBRIDISATION

1111 With low-cost renewable energy alternatives, storage and/or hybridisation are now a key part of the
1112 value proposition of CSP. While a thorough review of past work on energy storage for dishes is
1113 beyond the scope of this paper, included is a short discussion of options. As for energy generation,
1114 there are two main choices: either storage/hybridisation on the dish or at a central plant.

7.1　Dish mounted storage and hybridisation

1116 In the late-1970s and mid-1980s, JPL suggested coupling phase change materials (PCMs) to Stirling
1117 engines for energy storage [158, 159]. The concept of combining latent-energy transport and latent-
1118 energy storage is attractive because it maximises the exergetic efficiency of the entire system, and
1119 matches the isothermal input characteristics of the Stirling cycle engine. Both Infinia and Sandia
1120 proposed dish-mounted PCM/Stirling concepts that utilised the mass of the storage material as
1121 counterweight to the reflector (Figure 1) [160-162]. The Infinia concept used a sodium pool in direct
1122 contact with a NaCl/NaF PCM as an intermediary to the heater head of the Stirling engine. This helps
1123 overcome limitations with the poor conductivity of the salt. The Sandia concept utilised indirect heat
1124 transfer between the PCM and sodium, but used a metallic PCM (CuMgSi) to overcome potential
1125 heat transfer issues. CuMgSi was selected as the preferred phase change material (PCM) due to its
1126 good conductivity, high heat of melting and acceptable cost. In preliminary testing, corrosion of
1127 containment materials at the necessary temperature was a challenge. Unfortunately, both research
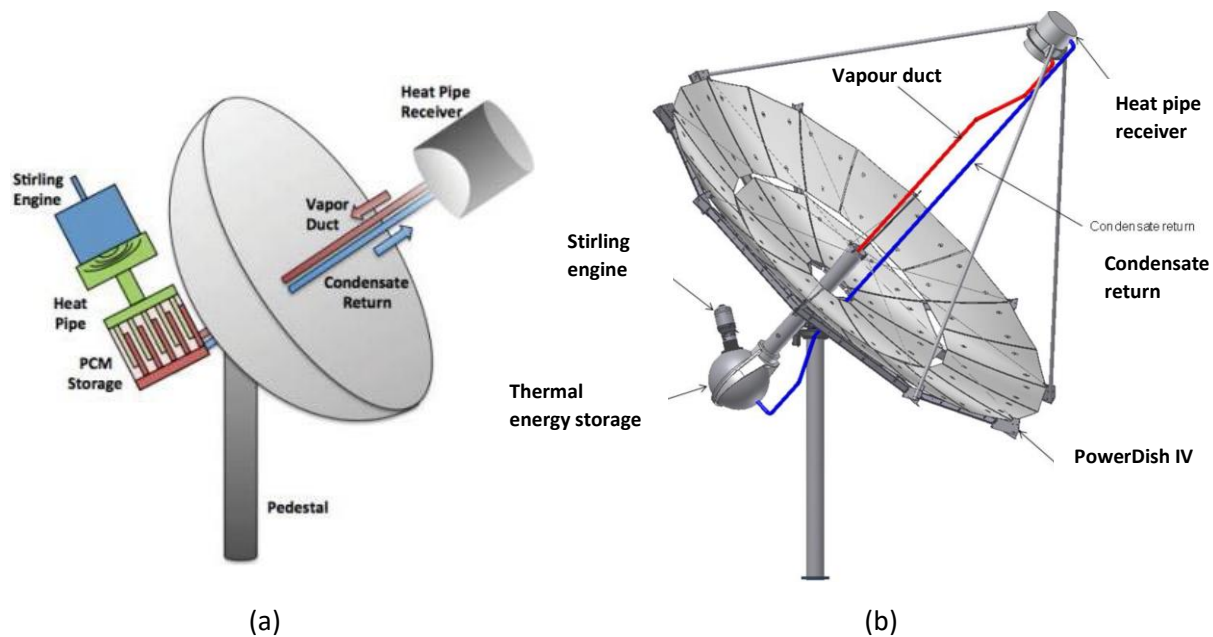1128 programs were terminated prior to testing on a dish.

1129

1130

(a)   (b)

1131   *Figure 40. Dish mounted PCM storage system for the Stirling power cycle as proposed by (a) Sandia*
1132   *[163] and (b) Infinia [162]*

1133   Dish mounted engines and receivers may be hybridised with fossil fuels, typically natural gas.
1134   Mendez et al. [164] present a review of the extensive body of past work with hybrid Stirling engines,
1135   which includes both directly illuminated hybrid receivers (ESOR, Sundish, BioDish) and hybrid reflux
1136   receivers (HYHPIRE, Sandia/NREL, Infinia). In addition, Cleanergy §5.31 is presently developing a
1137   hybrid version of its Sunbox Stirling engine as part of the BioStirling-4SKA project §5.33 [138].

1138   ## 7.2   Central storage and hybridisation

1139   Thermal storage at a central facility may be done using the conventional methods employed for
1140   other CSP systems, such as the two-tank system or a single tank thermocline system, with various
1141   storage media such as 'solar salt' (60% $NaNO_3$ and 40% KNO_3) or HitecXL (48% $Ca(NO_3)_2$, 7% $NaNO_3$,
1142   and 45% KNO_3) [165]. The challenge for dish power plants is the choice of HTF to transport energy
1143   from the dish field to the storage system. Synthetic thermal oil can be used for temperatures up to
1144   the 390°C. Examples of dish plants using oil as both the HTF and storage medium include the
1145   Shenandoah §5.4 and Kuwait §5.7. Lower temperature systems may use pressurised water for
1146   storage, as has been demonstrated with the ARUN dishes §5.24. For temperatures above 390°C the
1147   choice of HTF is more restricted. Solar salt is used as both HTF and storage media in state-of-the-art
1148   central receiver plants, and potentially could be used a dish field pipe network. However, the
1149   challenge of preventing the salt freezing in an extended pipe network, including through flexible
1150   couplings, is daunting. Liquid sodium is an alternative HTF, and with its excellent conductivity and
1151   lower melting point may be a better option than solar salt for a dish field. Reticulating pressurised
1152   air or other gases is also possible, in combination with a fixed storage bed. This has been
1153   demonstrated successfully at the solar tower system in Jülich which has an air receiver and storage
1154   in a ceramic brick bed at 680°C [166]. An integrated storage system with any of these high
1155   temperature HTFs - salt, sodium or air - is yet to be demonstrated in a dish field.

1156   There is significant experience with direct steam generation on dishes (§4.3). However, the
1157   integration of thermal energy storage (e.g. molten salt storage) with a DSG system is also
1158   challenging, due to the 'pinch point' problem, as described by Steinmann et al [167]. The pinch point

1159 is the result of a mismatch in heat transfer properties between the storage medium, with purely
1160 sensible heat exchange, and the steam, which undergoes latent heat transfer in both charging and
1161 discharging phases. Attempts to resolve the pinch point problem have included use of phase-
1162 change-material storage in series with sensible heat storage [167]. Coventry and Pye [168] proposed
1163 two alternative approaches, taking advantage of the more linear temperature-enthalpy
1164 characteristics of superheated subcritical steam and supercritical steam to reduce the temperature
1165 difference across the steam-salt heat exchanger [168]. A similar approach was proposed by
1166 BrightSource [169], where a fraction of the superheated steam was redirected from the power block
1167 to a steam-salt heat exchanger to charge the storage while in vapour phase, and then condensed
1168 while preheating feedwater returning to the receiver. This storage concept was originally proposed
1169 for BrightSource's Ashalim DSG power tower project (now under construction), but the storage
1170 component has since been removed [170].

1171 As discussed previously (§4.7) thermochemical storage is another promising option with dishes, but
1172 the only concept that has been tested is the ANU ammonia storage concept [47].

1173 Peterseim et al. [171] gave an overview of the many different options for hybridisation of centralised
1174 CSP systems. Dishes can be used in series or parallel with an auxiliary source of heat. In a series
1175 configuration, dishes may be used to superheat saturated steam, as was demonstrated for a subset
1176 of the dishes at LaJet's Solar Plant 1 §5.14, and proposed for HelioFocus' Wuhai plant §5.25.
1177 Operation of dishes in parallel with an auxiliary boiler is relatively straightforward from an
1178 engineering standpoint, and has been demonstrated at the ANU White Cliffs project §5.11.

8 OUTLOOK

1180 It is encouraging that there has been consistent evolution and improvement in parabolic dish
1181 designs, building upon the impressive burst of work from the dish pioneers in the late 1970s and
1182 early 1980s. Best practise dishes now have features such as lightweight structure, balanced design,
1183 high-quality, low-cost mirror panels, and can be deployed rapidly with little in-field labour. However,
1184 it is a difficult period for commercialisation of dish technologies, as energy storage has become
1185 essential to the value-proposition of CSP. There are a range of storage options for dishes, as
1186 discussed above, but there are technical challenges and other CSP technologies (troughs, power
1187 tower) have a stronger track-record in this area. Competing on price with photovoltaic technology
1188 without storage is a difficult sell. Several companies have come close to commercial success (SES,
1189 Infinia, Solar Systems) and built substantial demonstration plants, but have ultimately not
1190 succeeded. Recent commercial activities are shifting east (China, Pakistan, India, Middle East) and it
1191 may be in these markets that dishes regain a footing. There is a definite shift in research efforts in
1192 CSP toward higher-temperature technologies, to take advantage of high-efficiency power cycles and
1193 reduce cost. There is also a re-kindling of support for solar thermochemistry, as the world grapples
1194 with how to fully decarbonise the economy. Both these trends suit the dish technology, which is
1195 unrivalled in its performance at high temperature.

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