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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 practice 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 focuses 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.

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) (Blezinger, 1996), 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" (Church, 1890). 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 (Rannels, 1980), 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 (West and Larson, 1996), 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 Solar, Infinia), but it has not been easy, with strong competition from other renewable technologies and a difficult financial climate.

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

Over the years, several excellent reviews have been made solar parabolic dish developments (Jaffe, 1982; Panda et al., 1985; Stine and Diver, 1994; Mancini et al., 2003; Schiel and Keck, 2012), most with a focus on dish-Stirling systems. In this review, we focus primarily on the evolution of the parabolic dish design. A very brief summary of options for dish power conversion units (PCUs) and energy storage/hybridisation options is included for completeness.

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2. Parabolic dish description

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

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

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

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

3. Early dish developments

Funding in the US was particularly strong during the 1970s (West and Larson, 1996) and dish development was consequently driven by the US. The Solar Total Energy Project (STEP) was one of the earliest dish development projects, and in this project many fundamental aspects of dish design were analysed. From 1975 the Jet Propulsion Laboratory (JPL) began research into distributed CSP systems (Rannels, 1980; Marriott, 1983), and by the late 1970s a dedicated parabolic dish development project was underway. This included both parabolic dish and mirror panel technologies, as well as adaption of power conversion units for dishes, including Brayton, Stirling and organic Rankine cycles.

In the late 1970s a test site was established by JPL at Edwards Air Force Base in the Californian Mojave Desert (Hagen, 1980). A number of parabolic dishes were procured from private companies, including a dish from Omnium-G §5.5 and two so-called "Test Bed Concentrators" §5.6, which were adapted from existing satellite antennae designs, but incorporating JPL's newly developed spherical mirror panels (Goldberg, 1980; Argoud, 1980). These prototype dishes had excellent optical performance, and were the work horses for initial tests of engines, materials and the many subcomponents that make up a dish (Owen, 1983).

In France, the thermo-helio-electricity-kW (THEK) program was started in 1975 to develop parabolic dish power plants for a range of scales, at temperatures up to 325 °C (Audibert and Peri, 1981). Two different dishes were constructed during the period 1976–79 (THEK 1&2 §5.2).

However, relatively early in the parabolic dish development program it was realised that, despite plenty of previous experience with dish antennae for space tracking, there was a different cost and performance paradigm for design of a solar concentrator. JPL coordinated efforts to develop 'low cost' dishes, initiating the development of the so-called Parabolic Dish Number 1 and 2 (PDC-1 §5.9 and PDC-2 §5.10). The main companies involved – General Electric and Ford – were large corporations experienced with mass production techniques. Zimmerman (1980) of General Electric, noted the following three objectives:

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

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

From the early 1980s low-cost design was always a core objective for dishes, and dishes such as Vanguard (§5.12) and McDonnell Douglass (§5.13) built upon the knowledge gained from the PDC-1 and PDC-2 projects, albeit with many new design features. Two main styles of dishes emerged from these developments: glass-faceted concentrators and full-surface paraboloid concentrators (Stine and Diver, 1994). From 1984, management of the US dish program shifted from JPL to Sandia National Laboratories. The effort to reduce cost also led to some very novel concepts, and at the forefront was another style of dish, the so-called stretched-membrane concentrator. Although the concept had been around since the early 1970s (Bomin Solar §5.1), development of stretched membrane dishes accelerated in the mid-1980s. Schlaich Bergermann und Partners (SBP) built its first three stretched membrane dish prototypes in 1983, deployed first in Germany, then in Saudi Arabia. At 17 m diameter, these were large compared to other dishes at the time. A notable project in the US was the independently financed 700 dish 'Solar Plant 1', installed in 1984 by LaJet (§5.14). The LaJet dishes used the stretched-membrane concept but with multiple facets. At this time, the U.S. Department of Energy (DOE), through Sandia National Laboratories and NREL (then SERI) with private industry partners also began to develop stretched-membrane concepts, initially for heliostats (Alpert et al., 1991; Murphy and Tuan, 1987), but also for dishes from 1987 (SKI §5.17 and SAIC §5.19).

Another concept that was explored in the effort to achieve low cost was the so-called Stationary Reflector/Tracking Absorber solar collector (SRTA). In this concept, the reflector is a stationary segment of a sphere, and the absorber must be moved so its axis is always aligned with solar rays passing through the sphere centre (Steward and Kreith, 1975). The tracking requires motion of the absorber about two axes that intersect at the sphere centre. The receiver is an external, cylindrical linear receiver aligned to this axis. Cost advantages from the fixed reflector trade against performance disadvantages due to the higher cosine losses and lower concentration ratio. A small scale system was tested by E-systems (Steward and Kreith, 1975), and then demonstrated at larger scale in the Crosbyton project (§5.8), and later in Auroville, India (van den Akker and Lipp, 2004). A converse concept is the so-called Scheffler dish (Munir et al., 2010), where the focus is fixed and the reflector is a segment of a paraboloid with daily east-west tracking, and slow seasonal adjustment of declination. The tracking concept was described by Bomin Solar §5.1 in the early 1980s (Kleinwachter et al., 1983), but reintroduced in the present form by Wolfgang Scheffler in 2006 for solar cooking applications. The Thermax dish is based on this concept (§5.32).

As an alternative to a dish, a concentrator may utilise a lens. This has been particularly popular for concentrating photovoltaic applications (Philipps et al., 2016) because the conversion device can be a single cell and the Fresnel lens can therefore be small. Multifaceted lenses are relatively simple to make, and can be mounted on a single, larger solar tracking structure. For solar thermal applications, typically the receiver is large, and therefore lenses need to be large and are less suited to existing lens manufacturing methods. Also, the lens is more sensitive to slope errors, suffers chromatic aberration, and is limited to a longer focal length to diameter ratio than mirrors (necessitating a larger structure). However, advantages are that the receiver can be close to the ground and both it and its supports do not block the sunlight (Jaffe, 1982). E-systems (later renamed Entech) developed a conceptual design for an 11 m diameter concentrator based on a convex, dome-shaped acrylic Fresnel lens consisting of ten conical ring segments (O'Neill et al., 1982).

4. Power generation

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

Many different power conversion cycles have been considered for use with parabolic dish technology, with different working fluids. Dish mounted options investigated include organic Rankine cycles turbines with toluene, Stirling engines with hydrogen or helium, and open and closed air Brayton cycles. Dishes have also been used with concentrating photovoltaic modules. Ground mounted options investigated include power cycles suited to small power stations, such as Rankine cycle engines with steam, as well as power cycles suited to large power stations, such as conventional Rankine cycle steam turbines. Ground mounted systems require additional field piping networks and flexible or rotating couplings on the dishes, but do allow for large, centralised power blocks. For much of the history of dish development, dish-mounted power conversion units, or so-called 'dish-electric' systems, were considered attractive because of the modularity offered compared to parabolic trough and central receiver systems (Panda et al., 1985). Modularity meant flexible deployment of dish-electric systems in either small or large installations, and opened mass-production possibilities. However, modularity and scalability is also a feature of photovoltaic (PV) technology and today dish-electric systems need to contend with the low cost of PV. Thermal and thermo-chemical storage options, prevalent in other areas of CSP, may lead to a competitive edge over PV.

4.1. Stirling engines

Stirling engines are attractive for dish-electric systems because of their high power conversion efficiency (30–45%) at small scale (Stine and Geyer, 2001), with peak solar-to-electric efficiency exceeding 30% (Table 1). The Stirling cycle is in general well matched to the characteristics of dish operation. Concentrated solar flux from dishes can provide isothermal, high-temperature (typically 650–800 °C) heat with good efficiency. Stirling engines have been both coupled directly to dishes (Haglund, 1981) or indirectly via a sodium heat pipe (Zimmerman, 1981). Hybrid solar and gas systems have been tested to allow higher capacity factors and better performance during solar transients (Haglund, 1981). The main Stirling engines developments for dishes to-date are summarised as follows:

- The 25 kW 4–95 Mk II Stirling engine from United Stirling AB (USAB, a subsidiary of Kockums AB of Sweden) (Lopez and Stone, 1993). It was developed and tested with the TBC §5.6, Vanguard §5.12, MDAC §5.13, SES §5.20 and Ripasso §5.29 dishes, including the original Mk II engine and derivatives. All four records reported in Table 1 used versions of this engine.
- The 10 kW SOLO V-160, which originated from a different subsidiary of Kockums, Stirling Power Systems (SPS) (Baumuller et al., 1999), and was developed in partnership with Solo Kleinmotoren GmbH, later Solo Stirling GmbH. It was tested by Schlaich, Bergermann und Partner (SBP) on the DISTAL/Eurodish systems §5.16, by Sandia on the ADDS project §5.18 and is currently being developed by Cleanergy §5.31.
- The 22 kW STM 120 from Stirling Thermal Motors (STM) (now Stirling Power), that was deployed on the SAIC SunDish §5.19.
- The 3 kWe Stirling engine, developed by Infinia for its PowerDish system §5.27.

4.2. Steam engines

Both dish mounted and ground mounted steam engines have been investigated for parabolic dish applications. Jay Carter Enterprises (Nesmith, 1981) 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 (Demler, 1981). The Australian National University (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 (Kaneff, 1991) §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 to 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 (Fig. 1a) on a TBC dish §5.6, showing thermal efficiency in the range 80–88%[1] (Wright, 1981). At White Cliffs §5.11 steam receivers with a range of geometries were tested, with best thermal

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

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

Dish system	Original Stirling engine[a]	Gross efficiency (at generator)	Net efficiency (less parasitics)	Year
Vanguard §5.12 (Droher et al., 1986).	USAB 4-95	31.6%	29.4%	1984
MDAC §5.13 (Lopez and Stone, 1993)	USAB 4-95	31.4%	30.0%	1985
SES MPP §5.20 (Andraka and Powell, 2008)	USAB 4-95	–	31.25%	2008
Ripasso §5.29 (Ripasso Energy, 2013)	USAB 4-95	–	32%	2011

[a] Noting the engines were developed and improved, and often re-named, over time.

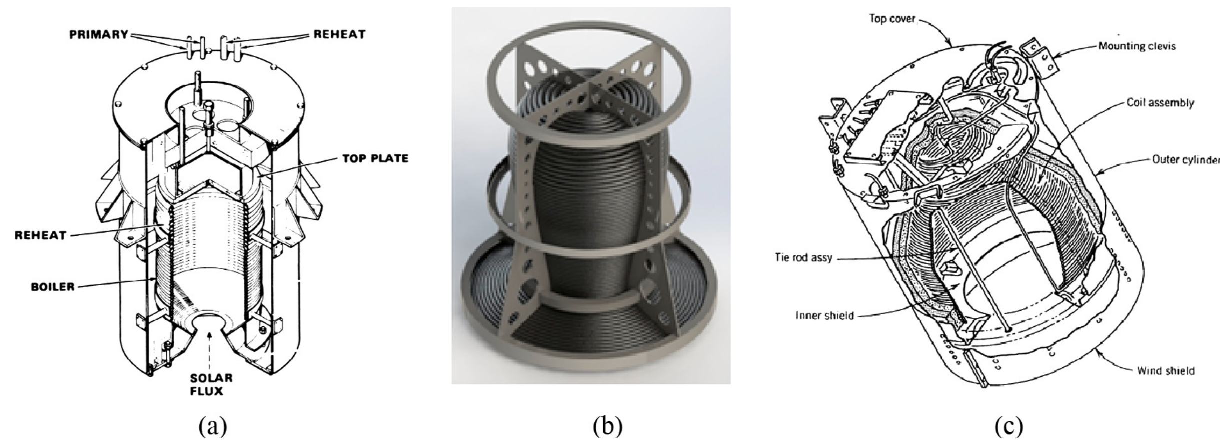


Fig. 1. Steam receivers from (a) Garrett (Panda et al., 1985) and (b) the ANU SG4 Big Dish (Pye et al., 2016), and an oil receiver from Shenandoah (Poehe, 1980; Kinoshita, 1981)

efficiency for a trapezoidal cavity of around 93% for 500 °C at the outlet. The ANU SG3 Big Dish steam receiver §5.21 was a 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 (Fig. 1b), and achieved 97.1% thermal efficiency in on-sun tests for steam >500 °C (Pye et al., 2016). 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 (Fig. 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.

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 (Boda, 1981), 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") (Panda et al., 1985). 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 (Brayton Energy, 2011). 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 (Garrett Turbine Engine Company, 1986) 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 (Chayet et al., 2011) and REhnu (Angel et al., 2014). In 2013, Solar Systems claimed approximately 30% solar-to-electric (AC) efficiency using 40% efficiency solar cells for a complete power plant system (Solar Systems, 2013), comparable efficiency to the 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 (Philipps et al., 2016). 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 (Lovegrove et al., 2004) (Fig. 2a). Steam reforming of methane has been demonstrated on dishes, in 2002, by CSIRO at Lucas Heights on a Solar Systems dish (Benito et al., 2003) and more recently, in 2011, by Pacific Northwest National Laboratory (PNNL) and Infinia (Wegeng et al., 2011) (Fig. 2b). Solar-to-chemical conversion efficiency of 69% was demonstrated (Zheng et al., 2015).

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 (Kleinwachter et al., 1983; Kleinwachter, 1982; Scott, 1990)

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 (Fig. 3a), based on rotating a segment of a paraboloid around the focal point. The dish concept, shown in Fig. 3b, was first described by Bomin in the early 1980s.

5.2. THEK 1 & 2 (Audibert and Peri, 1981; Audibert et al., 1987)

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

5.3. Raytheon (Panda et al., 1985)

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

5.4. Shenandoah (Stine and Geyer, 2001; Poehe, 1980; Kinoshita, 1981, 1983; Moore, 1983; Hunke and Leonard, 1983)

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

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

5.5. Omnium-G (Hagen, 1980; Zelinger, 1980)

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], and in the following few years installed a further thirteen concentrators around the world. The dish was a full-surface paraboloid with polished aluminium gores for the reflective surface (Fig. 7). Two types of receivers were developed, a direct steam generation receiver at 593 °C and an air receiver at up to 980 °C.

5.6. TBC 1 & 2 (Goldberg, 1980; Argoud, 1980; JPL, 1983; Diver et al., 1995)

The Test Bed Concentrators, or TBC 1 & 2 dishes, were 11 m diameter dishes, supplied by E-systems in 1979 and installed at Edwards Air Force Base (Fig. 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 frame, with a wheel-on-track type azimuth rotation, and a linear elevation drive. In 1984, the TBCs were moved to the Sandia National Laboratories in Albuquerque. In 1993 the mirrors had new thin glass mirrors bonded on top, as they had suffered large areas of silver corrosion. The corrosion was attributed to poor sealing, and the moisture retaining characteristics of the glass foam substrate.

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

Fig. 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.

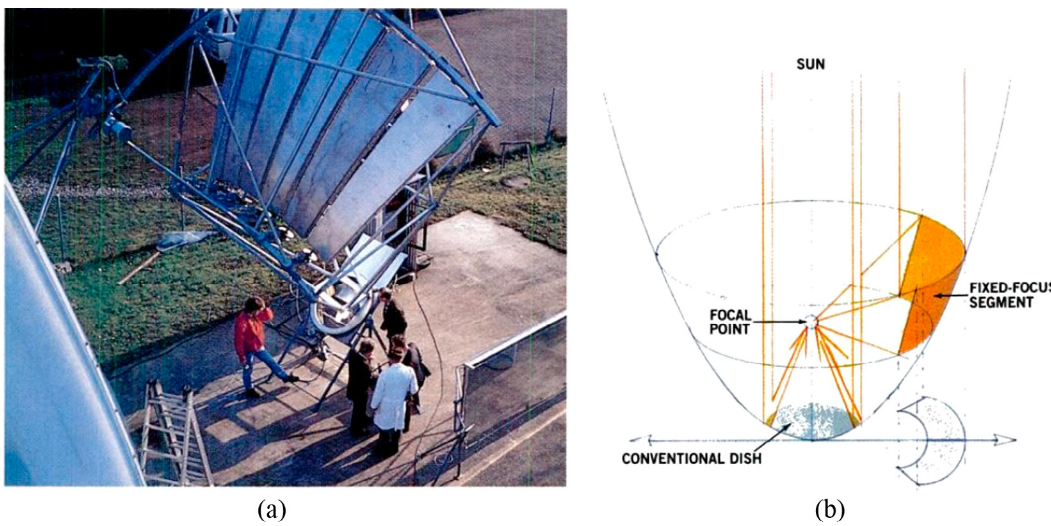


Fig. 3. (a) Bomin Solar's fixed-focus collector prototype and (b) diagram demonstrating the fixed-focus dish concept (Scott, 1990).

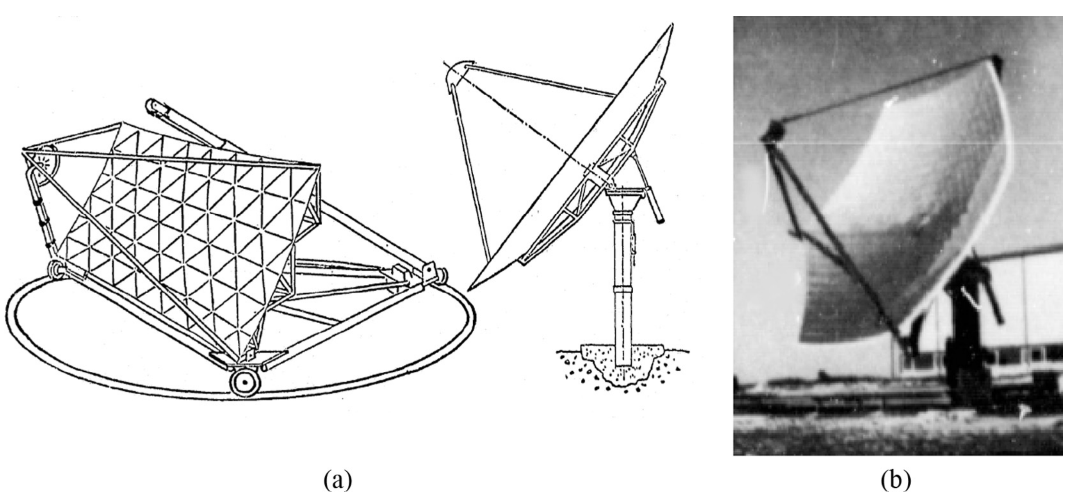


Fig. 4. (a) THEK 1 dish designs, and (b) a THEK 2 dish (Audibert and Peri, 1981).

5.7. Kuwait dishes (Zewen et al., 1981; Schmidt et al., 1980)

Messerschmitt-Boelkow-Blohm, together with the Kuwait Institute for Scientific Research (KISR) developed an 18 m^2 parabolic dish with first tests at KISR in 1979 (Fig. 9a). Subsequently 56 dishes were deployed in the desert region of Sulaibiya in Kuwait. The reflector was composed of six reinforced plastic sandwich panels, covered with very small (30 mm × 30 mm) mirror facets. A feature of this dish was that it was designed to rotated about the focal point, thereby avoiding the need for flexible piping to the receiver

Fig. 5. The Raytheon concentrator (Panda et al., 1985).

(Fig. 9b). The heat transfer fluid was a synthetic oil (Diphyl), and the balance of system incorporated thermal energy storage and an organic Rankine cycle for power generation.

5.8. The Crosbyton project (JPL, 1982)

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 (Fig. 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.

5.9. PDC-1 (Zimmerman, 1980, 1981; Stine and Geyer, 2001; Sobczak and Thostesen, 1982)

Designed by the space division of the General Electric (GE) company, the PDC-1 dish (Fig. 11) had as a 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

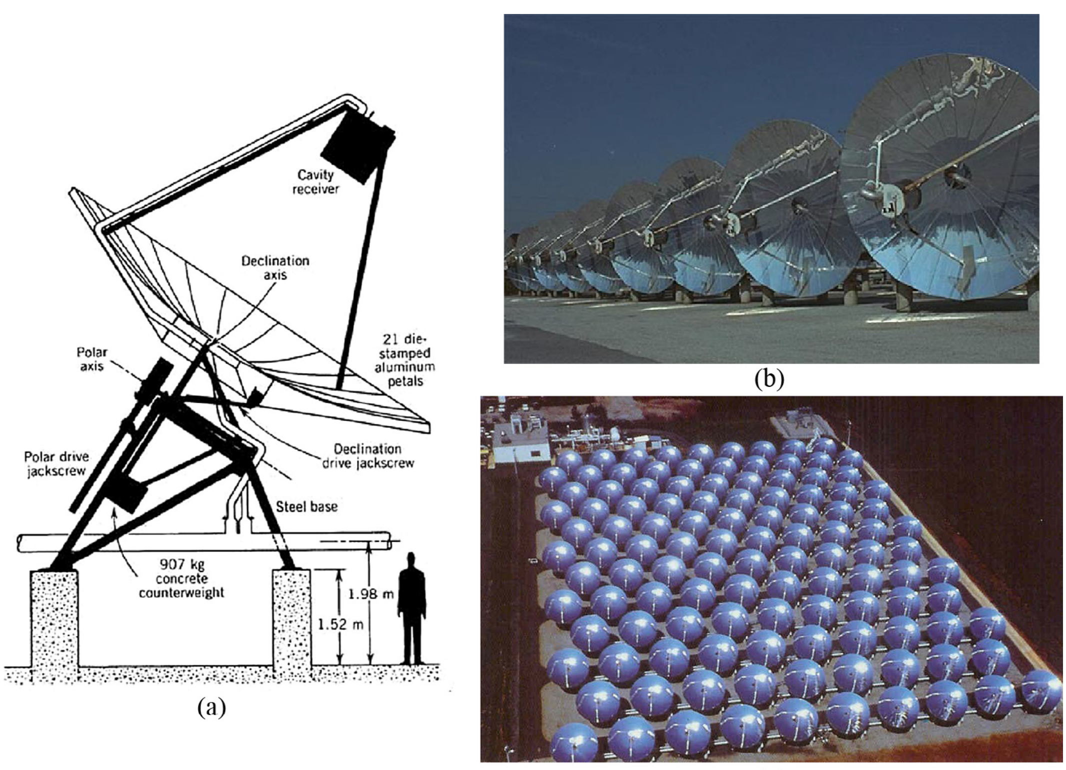


Fig. 6. The Shenandoah dish shown in (a) schematic view (Kinoshita, 1983) and (b and c) as installed.

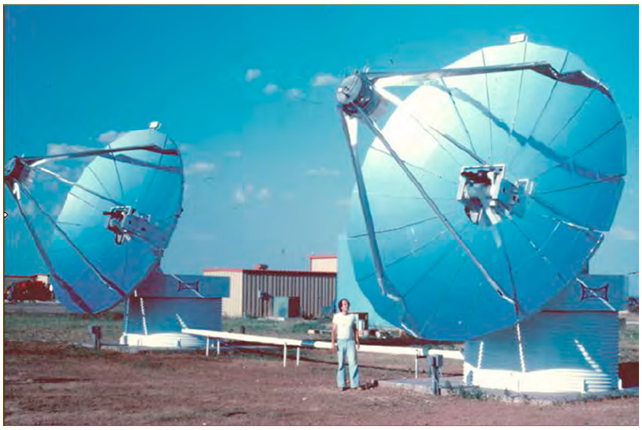


Fig. 7. The Omnium-G parabolic dish collector.

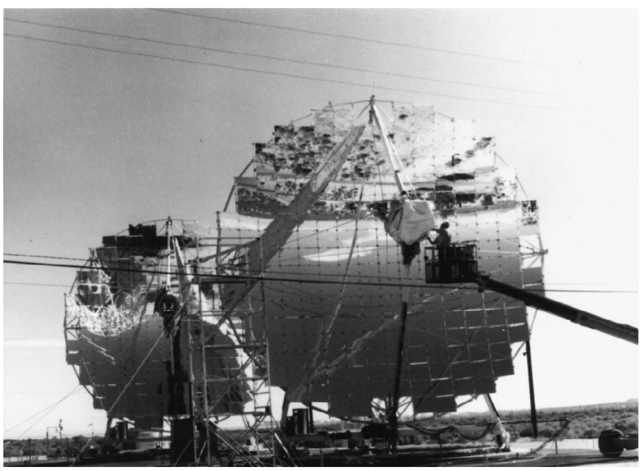


Fig. 8. The TBC 1 & 2 collectors installed at Edwards Air Force Base.

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

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

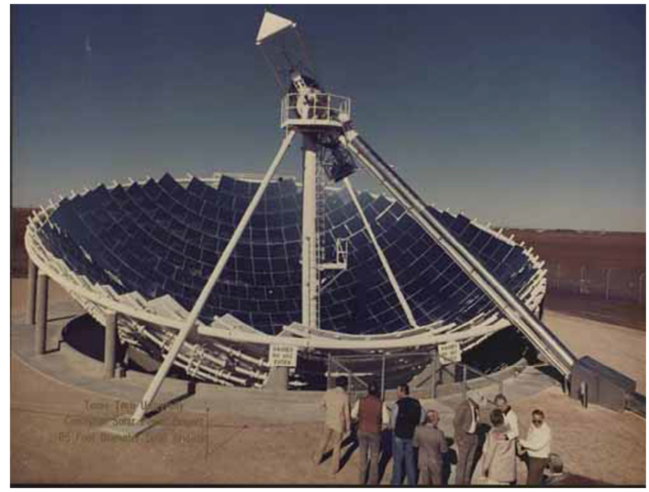
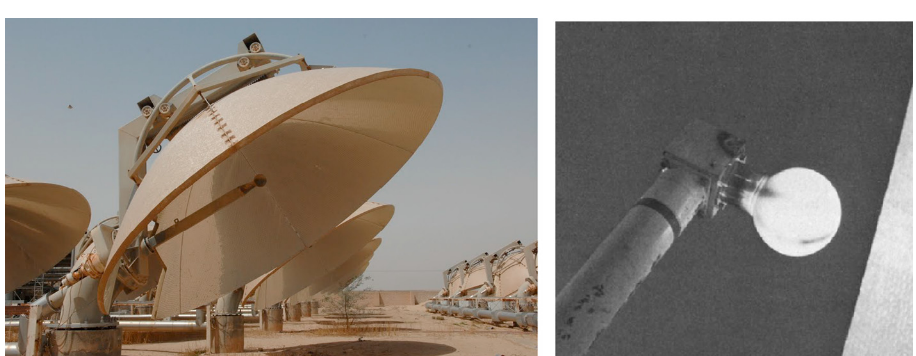


Fig. 10. The Crosbyton solar bowl. Photo: Texas Tech University.

The receiver deployed on PDC-1 was designed by Ford Aerospace and Communications Corporation and was a cavity type, direct-heated, once-through monotube boiler with toluene at supercritical pressure (see Fig. 11b and c). It was formed by a cylindrical copper shell and back wall with stainless steel tubing brazed to the outside surface, surrounded by insulation (Haskins, 1981). The copper shell had grooves machined into it to match the steel coil, to hold it in place and ensure good thermal contact. In tests in 1982, very good receiver thermal efficiency (radiation reflected to the receiver from the dish/energy absorbed by the fluid) was measured, at 95.2% (Babbe, 1982).

Barber Nichols designed and built the Organic Rankine Cycle (ORC) unit. Steady state tests were carried out in early 1981, then on-sun tests in late 1981 – early 1982. The complete ORC power unit was operated successfully over a range of operating conditions. Excessive bearing wear was experienced early in testing, but his problem was rectified (Barber, 1983). Predicted engine efficiency (net dc electrical output/thermal energy input) was about 26%, with relatively good part-load characteristics predicted to benefit annual performance, given the wide variety of solar operating conditions (Boda, 1981). Measured engine efficiency during testing in 1982 was 22.9%, a few percentage points below predic-



(a) (b)

Fig. 9. (a) Dishes installed in Sulaibyah, Kuwait; and (b) the fixed focal point oil receiver (Schmidt et al., 1980).

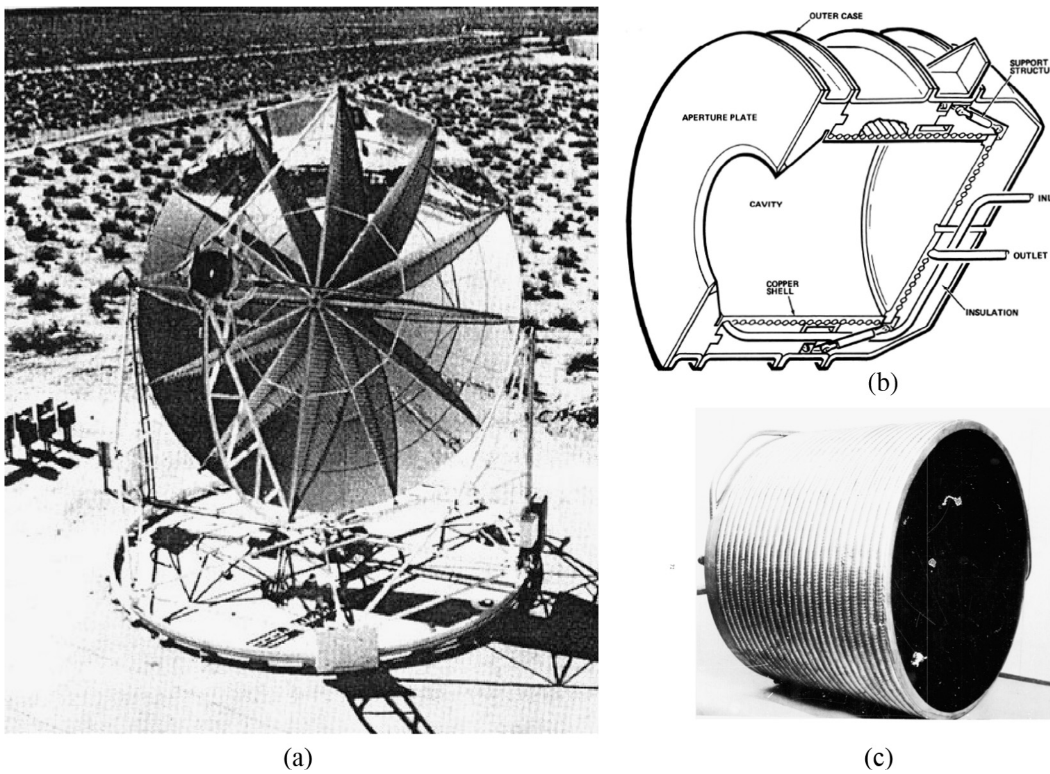


Fig. 11. (a) The PDC-1 installed at Edwards Air Force Base (Stine and Geyer, 2001); (b) schematic diagram and (Panda et al., 1985) (c) photo of the tubular toluene boiler that was attached to the front of the ORC power unit (Pons, 1981).

tion attributed to high pressure drop in the regenerator, and energy losses in the feed pump and alternator (Boda, 1982).

5.10. PDC-2 (Rafinejad, 1983; Bedard and Overly, 1981; Bell and Bedard, 1981)

The PDC-2 dish was a 12.2 m 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 (Fig. 12). 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 and 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.

5.11. ANU/White Cliffs (Kaneff, 1991; Bannister, 1991)

The Australian National University (ANU) White Cliffs project was a 14-dish installation built in 1980–81 to provide power to the remote town of White Cliffs in New South Wales (Fig. 13a). The dishes were constructed from a 5 m diameter fibreglass shell formed on a mould and tiled with 2300 small planar 2.5 mm thick

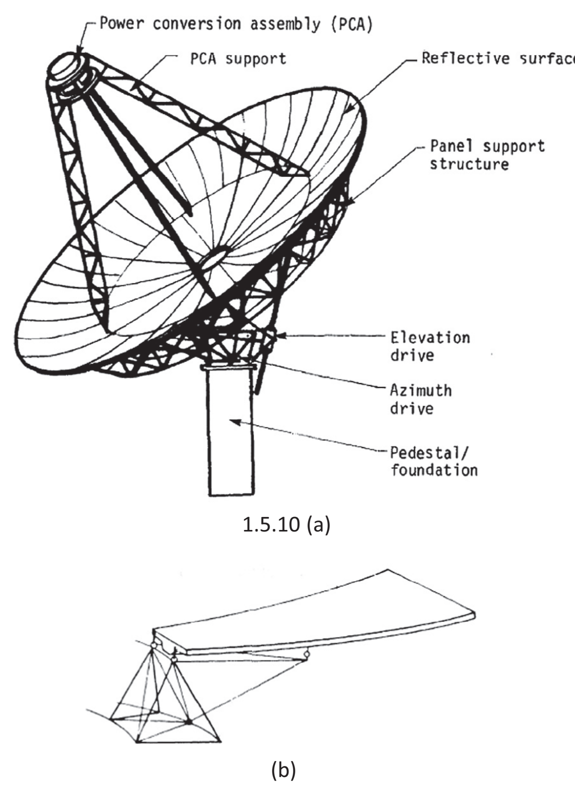


Fig. 12. (a) Schematic diagram of the PDC-2 dish (Rafinejad, 1983) and (b) the mirror facet and ring truss connection (Bell and Bedard, 1981).

glass mirror facets, each cut to conform to the paraboloidal shape. Dishes were transported to site as a wide load from Canberra to White Cliffs, with bridge clearance being a key consideration!

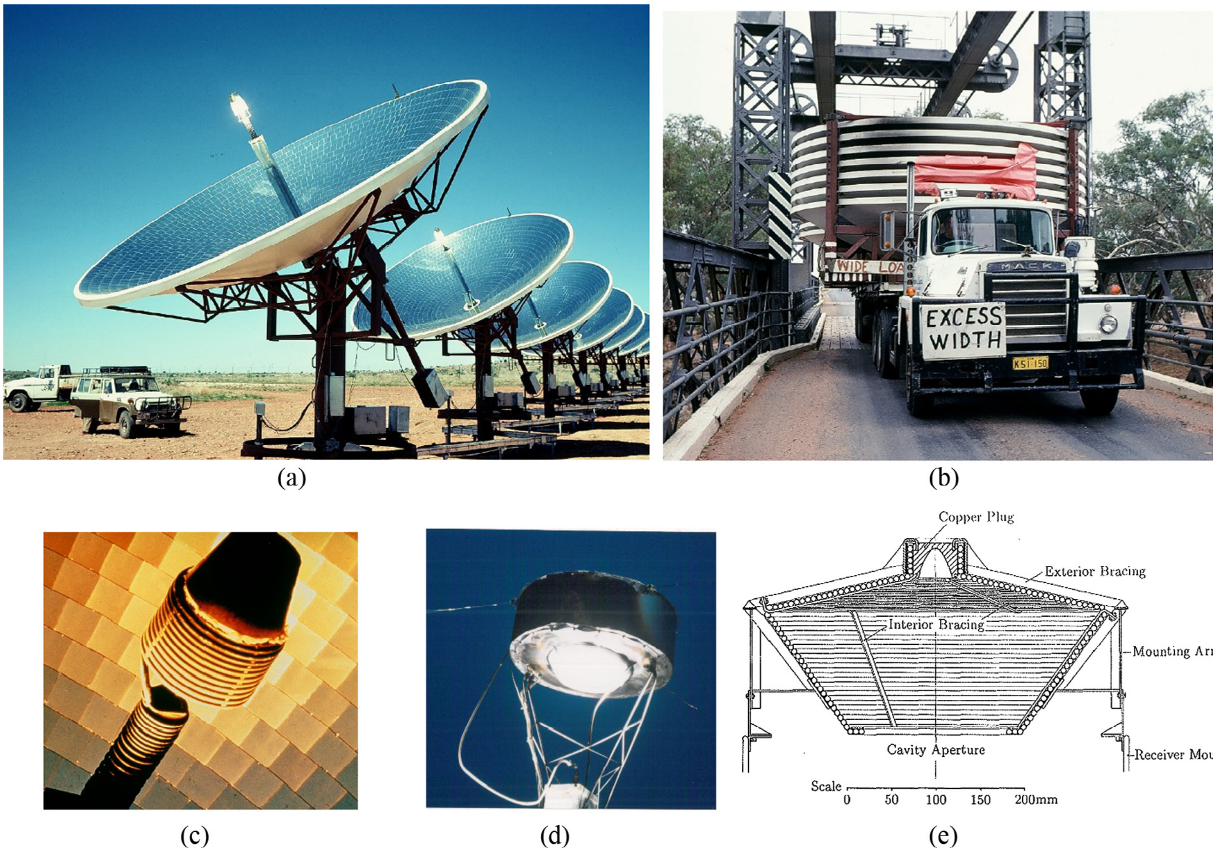


Fig. 13. (a) Dishes at White Cliffs; (b) dishes in transport to site; (c) the Mark 2 receiver on sun; (d) the Mark 10 receiver on sun; and (e) a schematic diagram of the Mark 10 receiver (Bannister, 1991). Photos: S. Kaneff and P. Bannister (ANU).

(Fig. 13b). The pedestal support included a novel "pipe-in-pipe" azimuth rotation. The advantage of this system is distribution of overturning loads along the pedestal pipe, rather than a load concentration at a drive at the top of the pedestal. A disadvantage is that that an extra pipe is required within the pedestal.

Direct Steam Generation (DSG) receivers on the dishes provided steam to a modified Lister HR-3 3-cylinder diesel engine. Steam was supplied to a chamber in the head of each cylinder. This adaption approach was to take advantage of the large existing market for diesel engines. The two major areas of development required were in the valve mechanism, and the oil-water treatment. The steam carried some oil droplets, which needed to be removed before the water was recirculated to the collectors. Engine efficiency was measured at 21.9% (415 °C, 4.1 MPa). A wide range of steam receiver geometries were tested at White Cliffs, with the Mark 2 and Mark 10 receivers shown in Fig. 13c–e. Thermal efficiency (radiation reflected to the receiver from the dish/energy absorbed by the fluid) was approximately 85% and 93% at 500 °C steam outlet temperature for these two receivers respectively (Bannister, 1991).

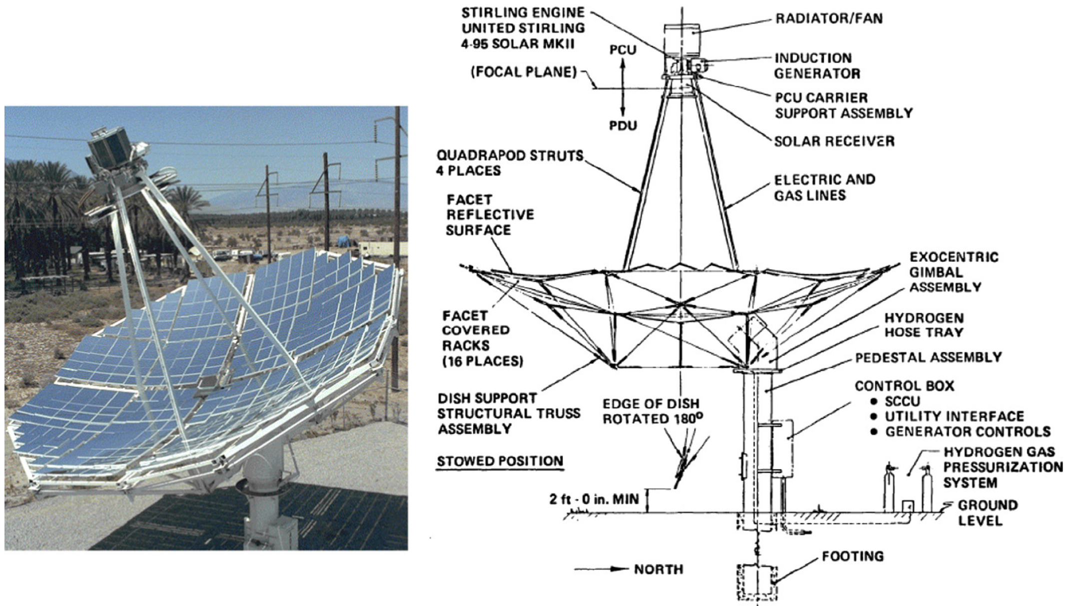
5.12. Vanguard (Stine and Diver, 1994; Droher et al., 1986; Livingston, 1983)

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" (Fig. 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 50 mm 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 (Fig. 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.

5.13. McDonnell Douglas (Lopez and Stone, 1993; Andraka and Powell, 2008; Laing and Schiel, 2001; Stone et al., 1999; Stirling Energy Systems, 2011; Sandia National Laboratories, 2009)

The McDonnell Douglas Astronautics Corp (MDAC) dish reflector consisted of 82 mirror facets to give an aperture area of 87.7 m^2 (Fig. 15a). The mirror facets were made of 0.7 mm glass mirrors bonded to a steel backing sheet, which was in-turn bonded to a stamped steel substrate (Diver and Grossman, 1998; Andraka, 2008). The backing sheet was stamped to a nominal curvature, then adhered to the stamped backing structure with thick layer of adhesive while mounted to a mould to define final curvature. The facets were a spherical contour, with 5 different radii of curvature to simulate a parabolic continuous surface.

The mirrors were mounted on curved truss subassemblies, linked together via a box truss. To minimise torque about the elevation pivot, it is located at the centre of mass between the receiver/PCU and the reflector, which is possible because of the discontinuous nature of the reflective surface. This feature - the cut-out mirror section, or "slotted dish" – has been replicated on many dishes since. For direct heated Stirling engine applications, the flux profile at the receiver needs to be quite uniform, and therefore individual mirror facets required careful canting. The central reflector support subassembly was open on the bottom



(a) (b)

Fig. 14. (a) The Vanguard dish and (b) schematic diagram.

side, which allowed pedestal mounting without interference. Azimuth tracking was via a pedestal-mounted gear drive, and elevation tracking was via a ball-screw jack. There was a sufficient range of movement to bring the receiver near to the ground for installation and maintenance.

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

Eight dishes were manufactured by MDAC in 1984/85. Originally three were installed at their Huntington Beach test facility in California, and one each at test sites in Barstow (Southern California Edison), Shenandoah (Georgia Power), and Las Vegas (Nevada Power). Since then, the original MDAC dishes have shifted around the US and the world to a variety of solar test facilities, including to the Aisin Seiki Stirling test facility in Japan, the Paul Scherrer Institute in Switzerland, ESKOM (SolarPACES, 2002) and now Stellenbosch University in South Africa.

The MDAC dishes were designed for operation with the USAB 25 kW 4–95 Mk II Stirling engine, and successfully operated for long durations. As an example, at least one Stirling dish operated every day from November 1984 until September 1988 (Lopez and Stone, 1993).

5.14. LaJet Energy Company (West and Larson, 1996; Panda et al., 1985; Schiel and Keck, 2012; Halbert, 1983; Schefter, 1985)

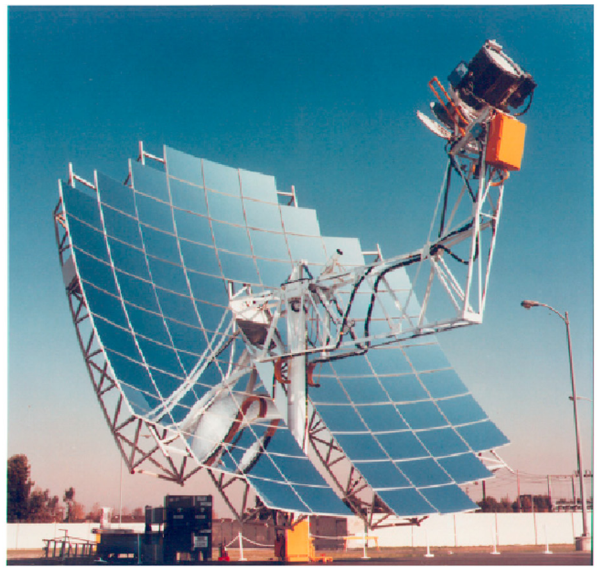
An example of a 'Fresnel-like' dish was developed by the LaJet Energy Company, a subsidiary of Louisiana Jet Petroleum Company. The open lattice structure was designed with the receiver as a counterbalance to the reflectors. The circular reflectors, each 1.5 m diameter, were constructed from polymeric 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 (Fig. 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, Fig. 16b) was then used by CPG for their 7 kW dish/Stirling development program in the early to mid-1990s (Mancini, 1998). 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.

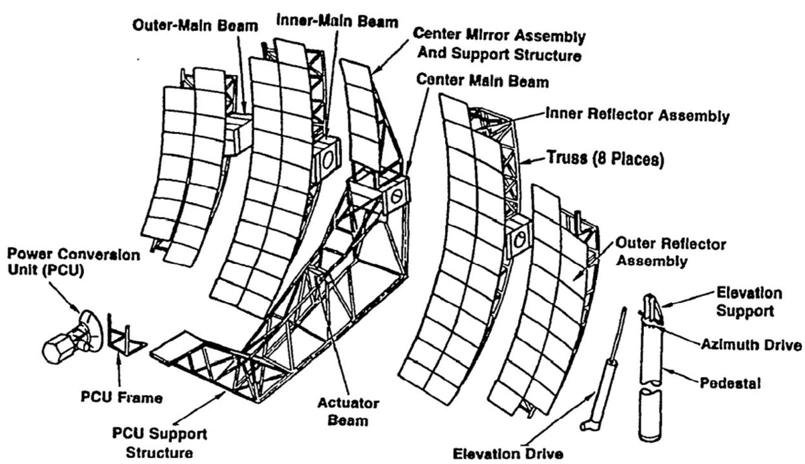
5.15. Power Kinetics, Inc.(West and Larson, 1996; Panda et al., 1985; Bannister, 1991; Hamad, 1987; Inall and Rogers, 1994)

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 (Fig. 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.

In 1987 PKI, in collaboration with the Australian National University (ANU), built a modified and much larger version of the square dish concept, a 300 m^2 collector (Fig. 17b and c) that was tested at Sandia, Albuquerque, throughout 1988. The reflector



(a)



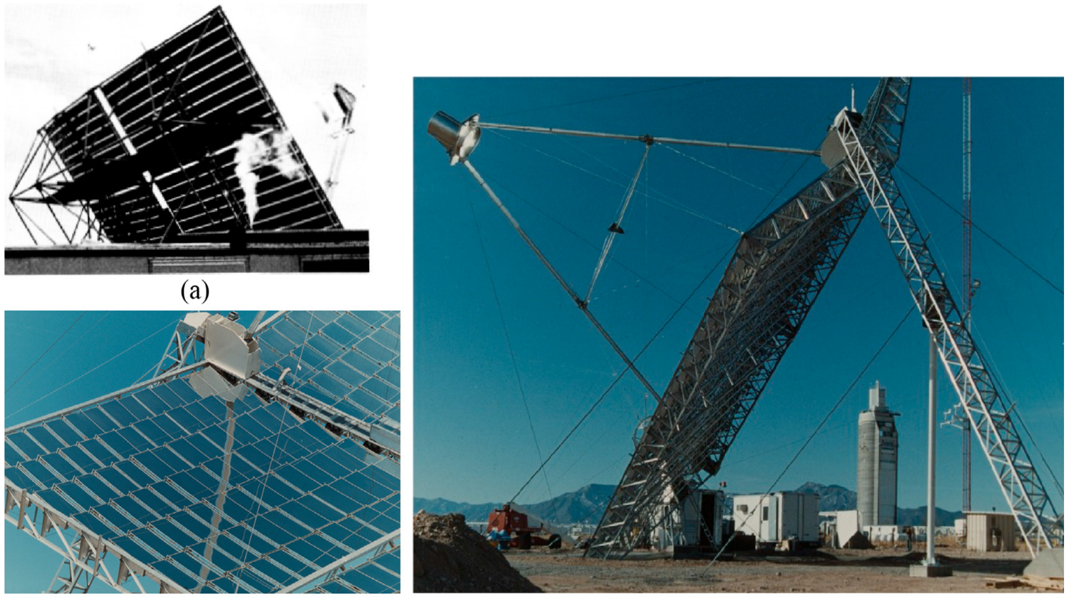
(b)

Fig. 15. (a) A McDonnell Douglas dish and (b) Schematic diagram of dish subassemblies (Lopez and Stone, 1993).

(a)

(b)

Fig. 16. (a) LEC-460 dishes at the 700-dish Solar Plant 1 at Warner Springs, California (Schefter, 1985); and (b) the modified version of the LaJet collector, the CPG-460 dish (Schiel and Keck, 2012).



(a) (b) (c)

Fig. 17. (a) The PKI "square dish" (Panda et al., 1985); and (b and c) the 300 m^2PKI/Molokai dish at Sandia National Laboratories, Albuquerque. Photo: S. Kaneff.

comprised 392 curved laminated glass mirror facets (developed by PKI), and had polar tracking, with the central beam aligned with the polar axis, and mirror assemblies extending outwards at 9° on either side. The reflector structure was supported by a tall polar pier (perpendicular to the axis of rotation) and a shorter equatorial pier. The piers were stabilised by tensioned cables from the foundations. The right ascension drive rotated the reflector about the polar axis, and the declination drive provided seasonal adjustment to the ganged mirror assemblies. Although motion was only required to be ±12° for solar tracking, wind feathering, defocusing and mirror protection positioning required more than 180° of motion. The receiver was a cavity absorber designed for direct steam generation. Some testing was performed at Sandia with a ground-mounted steam engine based on a modified 4-cylinder Lister diesel engine, similar to those at the White Cliffs project §5.11. The project was a precursor to a planned five dish installation at Molokai, Hawaii, that did not eventuate. Although acknowledged as an uneconomical design (Tennant-Wood, 2012), the project in part inspired the development of the ANU SG3 Big Dish (§5.21).

5.16. *DISTAL/Eurodish (Stine and Diver, 1994; Mancini et al., 2003; Mancini, 1998; Keck and Schiel, 2003; CIEMAT, 2001; Heller et al., 2001; Keck et al., 2006)*

German company Schlaich, Bergermann und Partner (SBP) started development of dish technologies beginning in the early 1980s, initially on the stretched-membrane dish concept. The concept (first described in 1965 (Alpert et al., 1991) is to use a continuous thin metal membrane stretched across a stiff circular drum, with a second membrane closing off the space behind. A vacuum is then applied to shape and hold the membranes in position. An advantage of this style of reflector is that it can be quickly defocused in case of emergency (e.g. tracking failure).

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

The next SBP dish, DISTAL I, was a similar stretched-membrane style but smaller (7.5 m diameter) and with a polar tracking method (Fig. 19a). To improve optical performance, it was shown that a parabolic shape could be maintained at the front membrane if the membrane was pre-curved and held under a slight vacuum. The method of curving the 0.23 mm thick stainless steel membrane was to stretch it beyond its elastic limit using a combination of water weights on the front and a vacuum at the back. Again, 0.7 mm glass mirror tiles formed the reflective surface. Six DISTAL I dishes prototypes were deployed for testing from 1989–92, including three at Plataforma Solar de Almeria (PSA). The DISTAL project tested an 8 kWe version of the Solo V-160 Stirling engine, and accumulated around 30,000 test hours operating three units at Plataforma de Almeria (PSA) in Spain daily from 1993 to 1997.

A second generation of the DISTAL concentrator (DISTAL II) was developed for use with the upgraded Solo V-161 Stirling engine (Fig. 19b). It was slightly larger (8.5 m diameter) and returned to the carousel-style azimuth-elevation tracking used for the SOLERAS project. Three DISTAL II prototypes started operating at PSA from 1996 to 1997. As part of this project the Solo Stirling 161 was redeveloped, with increased power and efficiency, and improved manufacturability and maintenance. A first hybrid version with combined solar and gas heat source was developed, and in 1999 successfully tested at PSA.

The EuroDish development was a joint-venture project between several European companies and research institutions, headed by SBP. To simplify shipping the dish, the stretched-membrane reflector from the DISTAL I and II projects was replaced by 12 identical gore-type sandwich panel mirrors, supported at the perimeter by a ring truss (Fig. 20). Each panel consisted of two 1 mm reinforced plastic layers with a 20 mm foam core. The panels were stiffened with a radial rib along the centre line, and thin glass mirrors were

Fig. 18. The SBP 17 m diameter stretched membrane dishes in Saudi Arabia (SBP, 2017).

adhered to the panel to form the reflective surface. A similar style tracking system was retained from the DISTAL II dish, but the drive units were redesigned to use standard steel rollers, spur gears and low cost servomotors. In 2001, the first prototypes were installed at PSA, Spain, equipped with the Solo V-161 Stirling engine, and since then EuroDish units have been deployed in many places around the world.

5.17. SKI (Alpert et al., 1991; Solar Kinetics, 1994; Grossman et al., 1992)

Solar Kinetics, Inc. (SKI) designed and built a 7-m diameter dish using the stretched membrane technology, and installed it at Sandia, Albuquerque in 1991 (Fig. 21). The dish is formed of two membranes. The front membrane is 0.3 mm type 304 stainless steel preshaped by plastic deformation to the desired parabolic shape by a combination of non-uniform loading (using with water on one side) and uniform loading (by a vacuum on the other side). The back membrane is made of a polyester cloth impregnated with PVC, and creates the sealed space for the vacuum. Once the front membrane is shaped, a separate polymer-film reflector is drawn down to the membrane with a slight vacuum. This approach allows the membrane to be replaced in the field. A ring around the membrane is held by a hub-and-spoke arrangement, similar to a bicycle wheel.

5.18. Sandia ADDS/WGA dishes (Mancini, 1998; Diver et al., 2003)

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

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

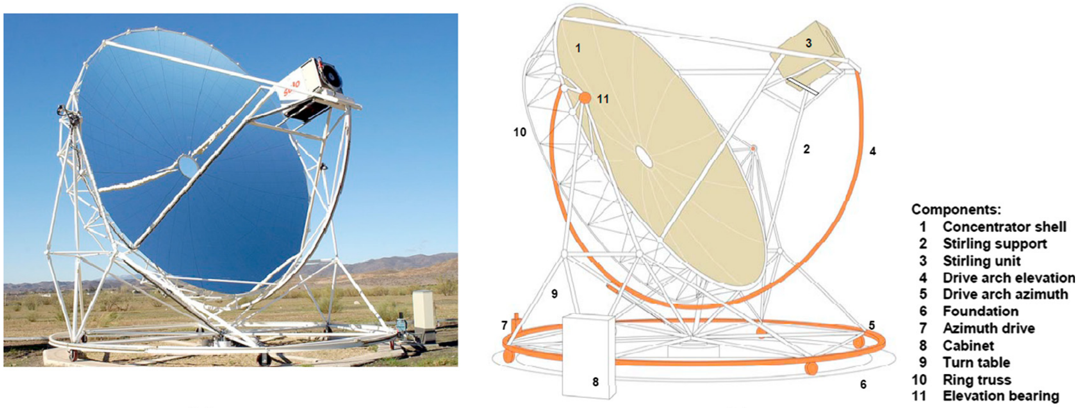
Sandia National Laboratories bought five solar Solo Stirling 161 engines and further developed and modified them as part of this project, including extensive testing between 2000 and 2002 (Diver et al., 2003). Improvements included better controls, improved isolation of hot parts, and adaption of the engine to use hydrogen instead of helium. Peak solar-to-electric efficiency was measured over 25%. The dishes and engines were being developed for both grid-connected and remote, unattended operation for off-grid applications such as water pumping. The primary purpose for development was to build a technology demonstration and development platform incorporating the best available technology. The on-grid performance was good, with a geometric concentration ratio of over 3000, which led to the off-grid development. Systems integration, optical improvement, and controls development were featured. The off-grid water-pumping unit is the only off-grid system demonstrated in the modern dish-Stirling era.

5.19. SAIC (Mancini et al., 2003; Laing and Schiel, 2001; Taylor and Davenport, 2007; Gallup et al., 1994)

Science Applications International Corporation (SAIC) began development of a dish-Stirling system in 1993, having worked on stretched-membrane concentrators for heliostats throughout the latter part of the 1980s. Their first dish prototype, the 12-panel FSM dish was tested in 1995 as part of the USJV program (Gallup et al., 1994). WGA developed the support structure, drives and

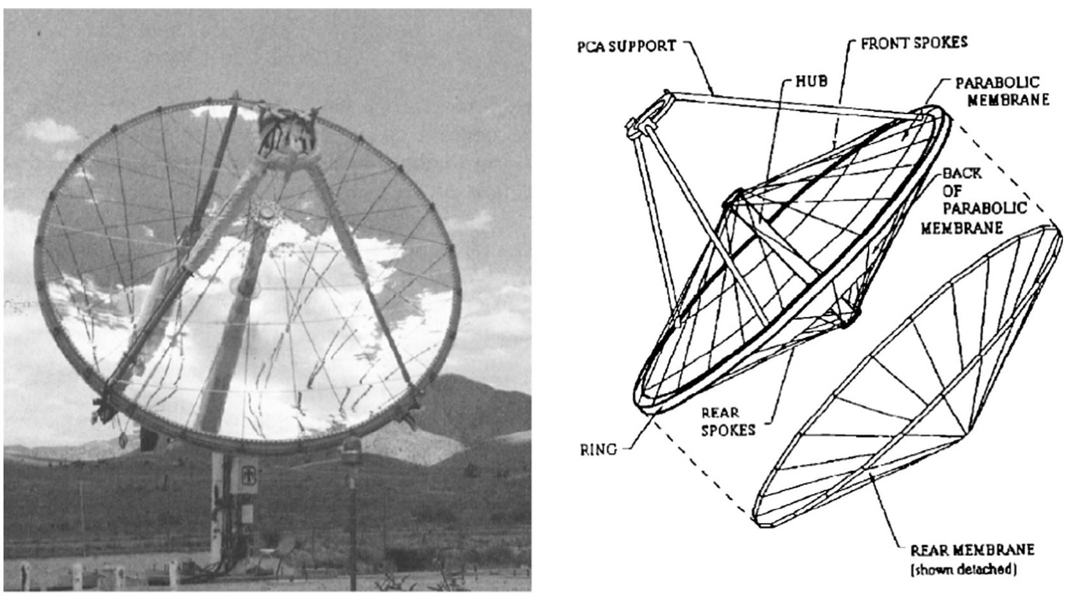
(a) (b)

Fig. 19. (a) The DISTAL I dishes (SBP, 2017) and (b) the DISTAL II dishes (SBP, 2017), both at PSA.



(a) (b)

Fig. 20. (a) The Eurodish SBP, 2017 and (b) a schematic diagram of the Eurodish (Keck et al., 2006)



(a) (b)

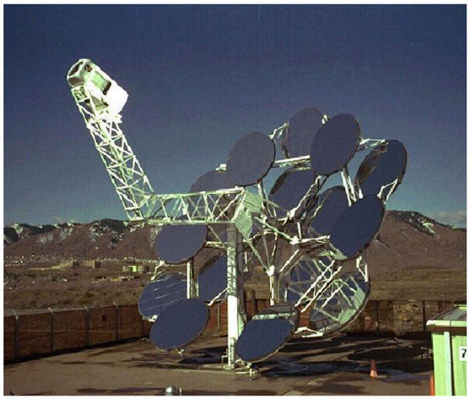
Fig. 21. (a) the SKI stretched-membrane dish (Alpert et al., 1991) and (b) schematic diagram showing its component (Grossman et al., 1992).

Fig. 22. ADDS dishes with Mod 1 (left) and Mod 2 (right) at Sandia (Diver et al., 2003). The Mod-2 system pictured is an off-grid water pumping unit.

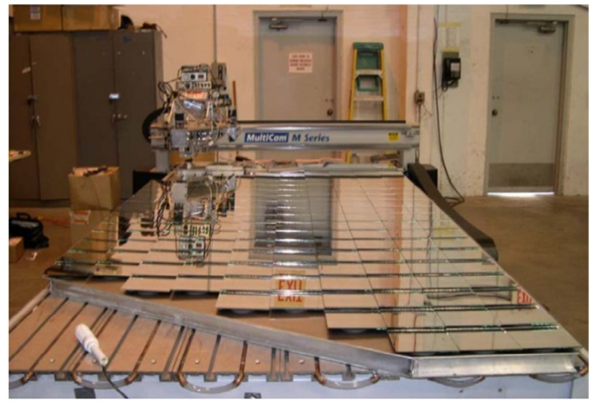
tracking control for this dish (Goldberg and Ford, 1991). From 1997 to 1999, SAIC developed and tested four prototype 22 kW "SunDish" dish-Stirling systems (Fig. 23a). Two were in Tempe, Arizona, another at the University of Nevada, Las Vegas (UNLV) and a fourth at NREL, Golden, Colorado.

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

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



(a)



(b)

Fig. 23. (a) SAIC dish at Salt River Pima-Maricopa Indian community (Laing and Schiel, 2001), and (b) mirror facet production equipment (Taylor and Davenport, 2007).

ror tiles were supported on a plastic puck that allowed the angle of the mirror relative to the flat substrate to be permanently set at any desired value by a robotic assembly system. The new mirror system was demonstrated at the dish at UNLV.

The SAIC dishes used the 22 kW STM 120 Stirling engine from STM (now Stirling Power) and logged many thousands of on-sun test hours. The engine used a direct absorption receiver and hydrogen as the working gas (Mancini et al., 2003; Laing and Schiel, 2001). In 2003, a quartz window was included to allow recuperation of exhaust gases and to partly homogenise the light, but it experienced a series of failures (Taylor and Davenport, 2007).

5.20. Stirling Energy Systems (Stirling Energy Systems, 2011)

Stirling Energy Systems (SES) was founded in 1996 to commercialise the MDAC technology, acquiring the rights to the dish and a license to the USAB 4-95 Mk II engine Stirling engine. In the late 1990s Boeing Company (who had acquired MDAC) and Kockums teamed with SES to refurbish the engines and recommenced testing of the dish-Stirling systems at the Huntington Beach facility. A study of the mirror panel optics (Stone et al., 1999) concluded that after 14 years in the field, the mirror panel optics were approximately the same as when manufactured.

The first SES-built dish was installed in 2004 at the site of technology partner Sandia National Laboratories in Albuquerque (Andraka and Powell, 2008); and dubbed the "Model Power Plant" or MPP (Fig. 24a). It was an adaption of the MDAC dish, with a modernised control system and new mirror facets based on a sandwich construction of two aluminium face sheets, aluminium honeycomb core, and a thin glass mirror bonded to the front, as developed by Sandia for ADDS (§5.18). This marked the start of 5 years of value engineering, iterating and improving the design to lower cost and improve performance of both the dish and the Stirling engine power conversion unit. Five second-generation MPP dishes were added in 2006, with an emphasis on systems engineering and installation processes. In January 2008 a new performance benchmark of 31.25% net solar-to-electric was set on a cold, high DNI day (Andraka and Powell, 2008) with an MPP dish and a USAB 4-95 Mk-II engine. In 2009, a further four dishes were installed at Sandia with the unveiling of the "SunCatcher™" design (Fig. 24b). The 25 kWe SunCatcher had a significantly modified reflector structure, with radial trusses and larger, trapezoidal mirror gore facets based on the Sandia ADDS, using a stamped steel mirror construction with a thin glass reflective surface, similar to the original MDAC dishes. The improvements resulted in fewer parts, and a 2.3 tonne mass reduction (~29%). The SunCatcher also featured a driven steel foundation that eliminated concrete and significant field labour. In all, 11 SES dishes were installed at Sandia, including a refurbished MDAC system, 6 MPP systems, and 4 SunCatcher systems. In March 2010, the 1.5 MWe Maricopa Solar plant was commissioned at Peoria, Arizona, with 60 SunCatcher dishes (Fig. 24c).

Unfortunately, in September 2011, SES filed for bankruptcy, and the plant was decommissioned. The 60 Maricopa dish assets were bought by UK company United Sun Systems International (headquartered in Gothenburg) in 2012 in a joint venture with a Chinese/American company (United Sun Systems, 2017). 30 were sent to China, and the rest were held in storage in Phoenix (although some have now been on-sold) (Jacobsson, 2017). The 11 dishes at Sandia were acquired by Stirling Power of Anne Arbor. The four SunCatcher's were disassembled and moved for later development. The MDAC and four MPP dishes were scrapped, while two MPP dishes remain at Sandia. In 2012 Stirling Power (formerly Stirling Thermal Motors then Stirling Biopower), a subsidiary of Chinese company, Xiangtan Electric Manufacturing Company (XEMC), acquired SES's Stirling engine assets (Stirling Power, 2017).

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 (Kaneff, 1992). 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 (Fig. 25). 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) (b) (c)

Fig. 24. (a) The SES MPP dish (Andraka and Powell, 2008) and (b) SES SunCatcher (Sandia National Laboratories, 2009), both at Sandia, Albuquerque, and (c) the Maricopa solar plant [Photo: CSPworld.org].

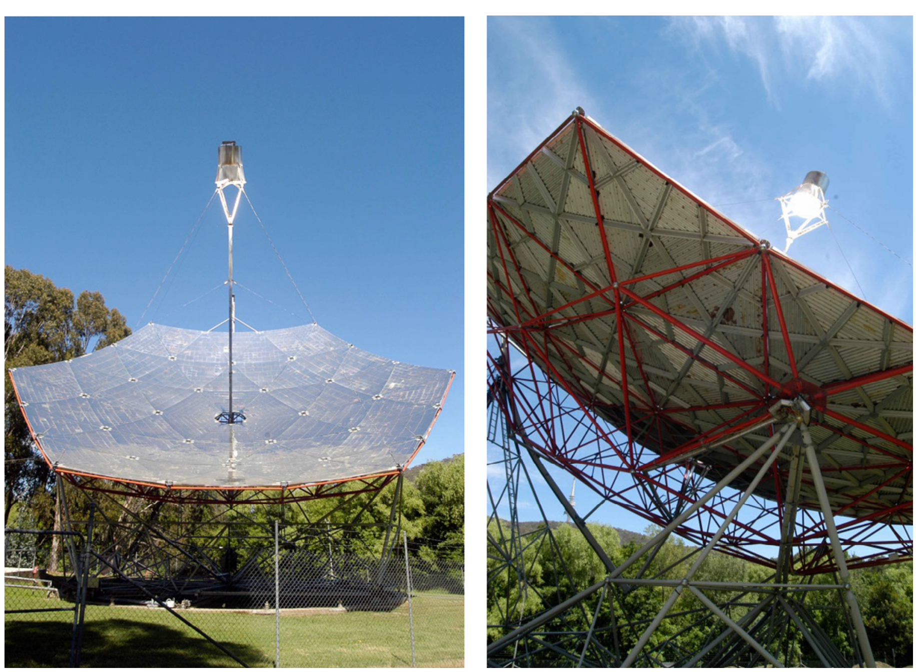


Fig. 25. The SG3 Big Dish at ANU. Photos: Chris Holly.

A second SG3-style Big Dish prototype was deployed at the Ben Gurion University in Israel soon after SG3 was built.

5.22. SG4 Big Dish (Pye et al., 2016; Lovegrove et al., 2009, 2011)

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 (Fig. 26a and b). SG4 retained the concepts of large size (Lovegrove et al., 2007) 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 concern about manufacturing tolerances (Fig. 26c). The reflective surface was formed by 380 identical 1.17 m $\times$ 1.17 m 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 (Lovegrove et al., 2011). 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 (Pye et al., 2015). 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 (Pye et al., 2016).

5.23. Solar Systems (Verlinden et al., 2001, 2006; Lasich, 2002)

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 (Fig. 27). The reflector structure was a radial truss arrangement, overlayed with a rectangular mesh for mounting the mirrors. Each dish had 112 identical 1.1 m $\times$ 1.1 m 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 (Lasich, November 2003). 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 (Lasich, 2001). 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 (Verlinden et al., 2006). 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 (Solar Systems, 2013).

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.

5.24. ARUN (Clique Solar, 2016)

The ARUN™ 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 employing a counterweight for balance. The company presently offers three different models, the ARUN 30, 100 and 160 (with aperture area 34 m^2, 104 m^2, 169 m^2 respectively, Fig. 28). The dishes are designed for various heat transfer fluids including steam, hot oil, hot water and hot air at temperatures up to 350 °C and pressures up to 25 bar. Commissioned in 2006, the first industrial project was a single dish providing pressurised hot water at 180 °C to a dairy in Latur, India. Since then dishes have been installed for a variety of process heat applications in India.

5.25. HelioFocus (SBP, 2017; Keck et al., 2012, 2015)

The HelioFocus 500 m^2 faceted dish concentrator concept was developed in partnership with SBP from 2008. The first dish prototype was installed in Dimona, Israel, in 2012 (Fig. 29a). The reflector employed 219 mirror facets, each 1.5 m $\times$ 1.5 m, arranged in a Fresnel-like array. The steel reflector structure had a stiff torque box at the base, with seven 18 m long cantilever arms extending to the top of the dish, linked transversely by circular purlins. The mirrors were bent glass, supported at five points and mounted on the purlins. Tracking was carousel-style with a central hub for lateral guidance, a steel base ballasted with concrete to prevent overturning, and four wheel bogies mounted on a circular crane rail. Both azimuth and elevation axis were driven by hydraulics, with a 2-cylinder pilgrim step drive on azimuth rotation, a little similar to the SG3 Big Dish walking ram system, but allowing continuous motion. A second prototype, the 'Orion' dish, was designed with some modifications, and installed at the 8-dish Orion plant near Wuhai, Inner Mongolia in 2013 (Fig. 29b). The Wuhai installation had an air receiver, and reticulated hot air for centralised boosting of a steam cycle, but the plant was never commissioned. HelioFocus was formally shut down in early 2017 (Karni, January 2017).

5.26. Southwest Solar (Hayden et al., 2012; Southwest Solar Technology, 2017; Hayden, January 2017)

The 320 m^2 SST Big Dish was developed by Southwest Solar Technologies Inc. and installed in Phoenix, Arizona, in 2011 (Fig. 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 (Fig. 30b and c). The reflector consists of 12 mirror composite mir-

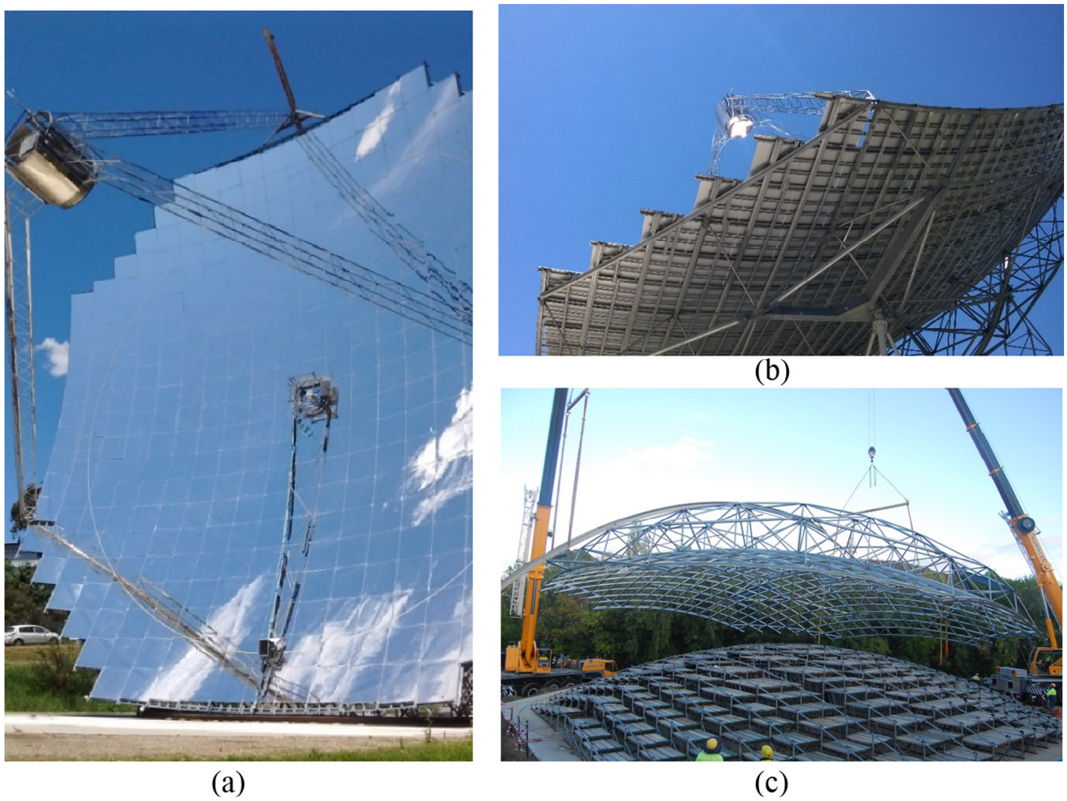


Fig. 26. (a and b) The SG4 Big Dish at ANU, and (c) lifting the dish reflector frame a jig during construction. Photos: Joe Coventry.

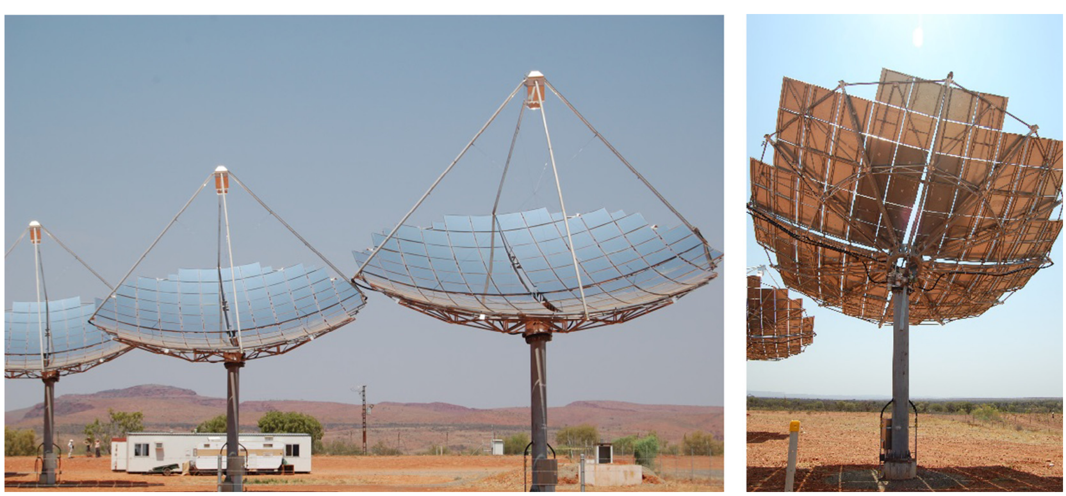


Fig. 27. Solar Systems CS500 dishes at Umuwa, central Australia. Photos: Joe Coventry.

ror 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 (Baldry and Taylor, 2016).

5.27. Infinia PowerDish (Schiel and Keck, 2012; SBP, 2017; Prinsloo and Dobson, 2015; Infinia, 2012; US Department of Energy, 2007; Andraka, 2011)

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 25 kWe solar-electric Stirling power system for NASA and DOE for a solar dish plant, and in 1991–94 developed a hybrid solar/nat-

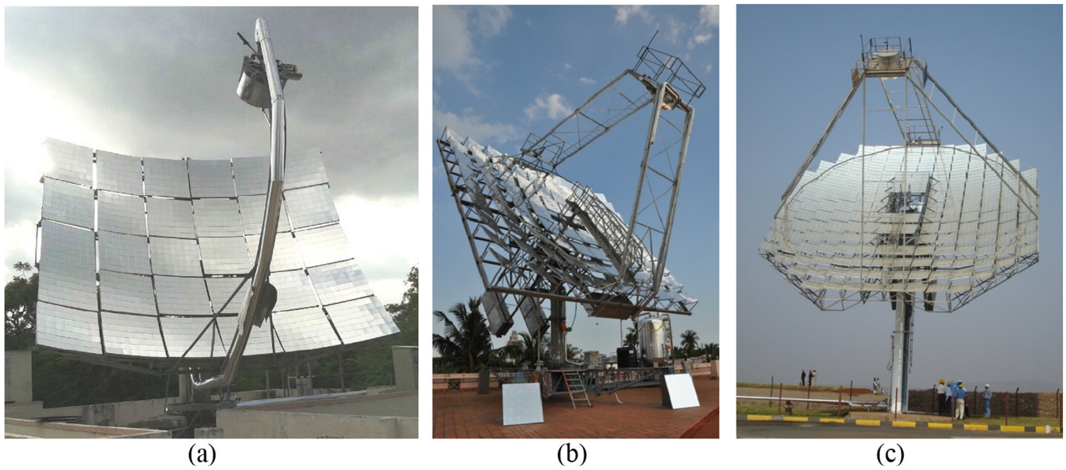


Fig. 28. Fresnel-type dishes from Clique Solar (a) ARUN 30, (b) ARUN 100, and (c) ARUN 160 (Clique Solar, 2016).

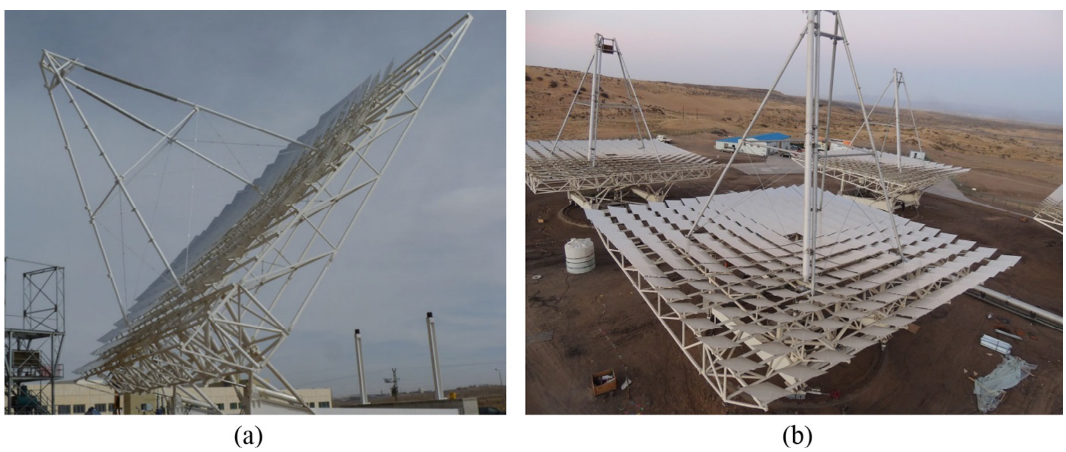


Fig. 29. (a)The first HelioFocus dish prototype in Dimona, Israel and (b) the pilot plant near Wuhai, in Inner Mongolia. Photos: SPB (2017).

ural gas power system for NREL. In 2001, a 1 kWe Infinia Stirling generator operated 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 (2015). 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 (Fig. 31a and b). The mirrors were thin glass bonded to 6 glass fibre reinforced plastic petal-shaped facets. 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 of the entire 25-year life span. 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 (Fig. 31c and 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 were mounted at three points to the circumferential framing. The elevation axis mount was laterally offset from the azimuth axis mount to allow the necessary range of movement (Fig. 31e).

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.

5.28. ZED Solar (Jamil and Ali, 2016; Ali et al., 2016)

The Solar Invictus dish from ZED Solar (designed by AEDesign) is a 9 m diameter pedestal mounted dish (Fig. 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.

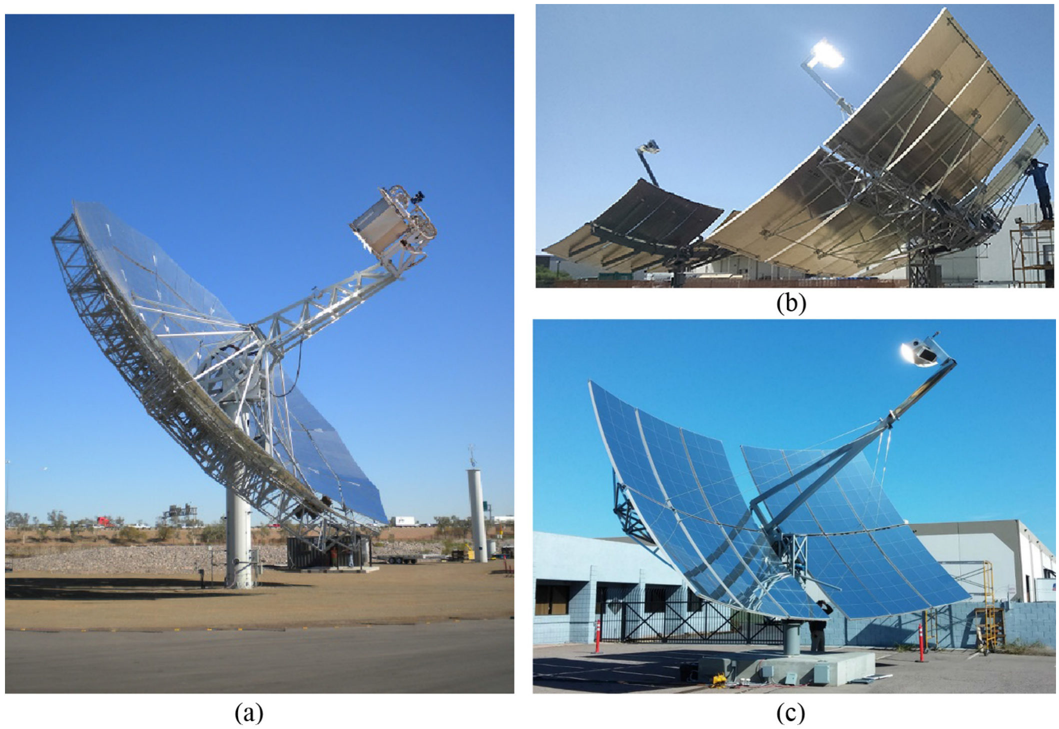


Fig. 30. (a) The 320 m^2 SST Big Dish installed in Phoenix, Arizona, (Southwest Solar Technology, 2017) and (b and c) the 54 m^2 SST Dish 600 (Southwest Solar Technology, 2017; Hayden, January 2017).

5.29. Ripasso (Ripasso Energy, 2013, 2016; Titan Tracker, 2017)

Ripasso was formed in 2008 primarily to develop and commercialise a Stirling engine licenced 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 (Fig. 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 (Fig. 33b). The design of the reflector and lightweight 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 two semi-circular ring beams, and passing over rollers mounted directly above the azimuth rotation wheels. The cradle has a counterweight at the rear of the dish for balance.

5.30. Great Ocean Energy (Great Ocean Energy, 2017; Nilsson et al., 2016; CSP Plaza, 2017)

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 (Fig. 34a). The plant comprises 10 dishes each with a 10 kWe 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 Cleanergy for a prototype installation in Seville, Spain. In 2015, GOE installed two 25 kW dish-Stirling prototypes in Zhang Jiagang, in Jiangsu Province (Fig. 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.

5.31. Cleanergy (Nilsson et al., 2016)

Cleanergy was established in 2008 as a developer of Stirling engines. As discussed above, initial testing of the Cleanergy Stirling engine employed dishes procured from others, but in early 2016 Cleanergy deployed its own dish design at its demo park in Dubai (Fig. 35). The dish is of a similar design to the other ZED Solar/AEDesign dishes at the Dubai facility, but a little larger to match increases in input thermal power requirements of Cleanergy's Sunbox Stirling engine.

Cleanergy's engine development is based on the Solo V-161 engine, which it acquired from Stirling Systems AG and EBM of Switzerland in 2008 (who themselves had bought the technology from Solo Stirling GmbH in 2007). The engine has since been developed further and new models released (C11S, Sunbox) (Nilsson et al., 2016). The 11 kW C11S unit has modernised electronics plus other tweaks and accumulated 20,000 operational hours over the first 12 months of testing at a 10 dish installation installed in Dubai by 2015 (Nilsson et al., 2016). Further improvements are ongoing, including improvement of the working gas channel to improve the gas cooling (Nilsson, 2017).

5.32. Thermax (Thermax, 2017)

The 16 m^2 Thermax SolPac™ D160 (Fig. 36) is a so-called Scheffler dish (Munir et al., 2010), where the focus is fixed and the reflector is a segment of a paraboloid with daily east-west tracking, and slow seasonal adjustment of declination, as introduced earlier (§3). The Thermax reflector geometry is set based solar declina-

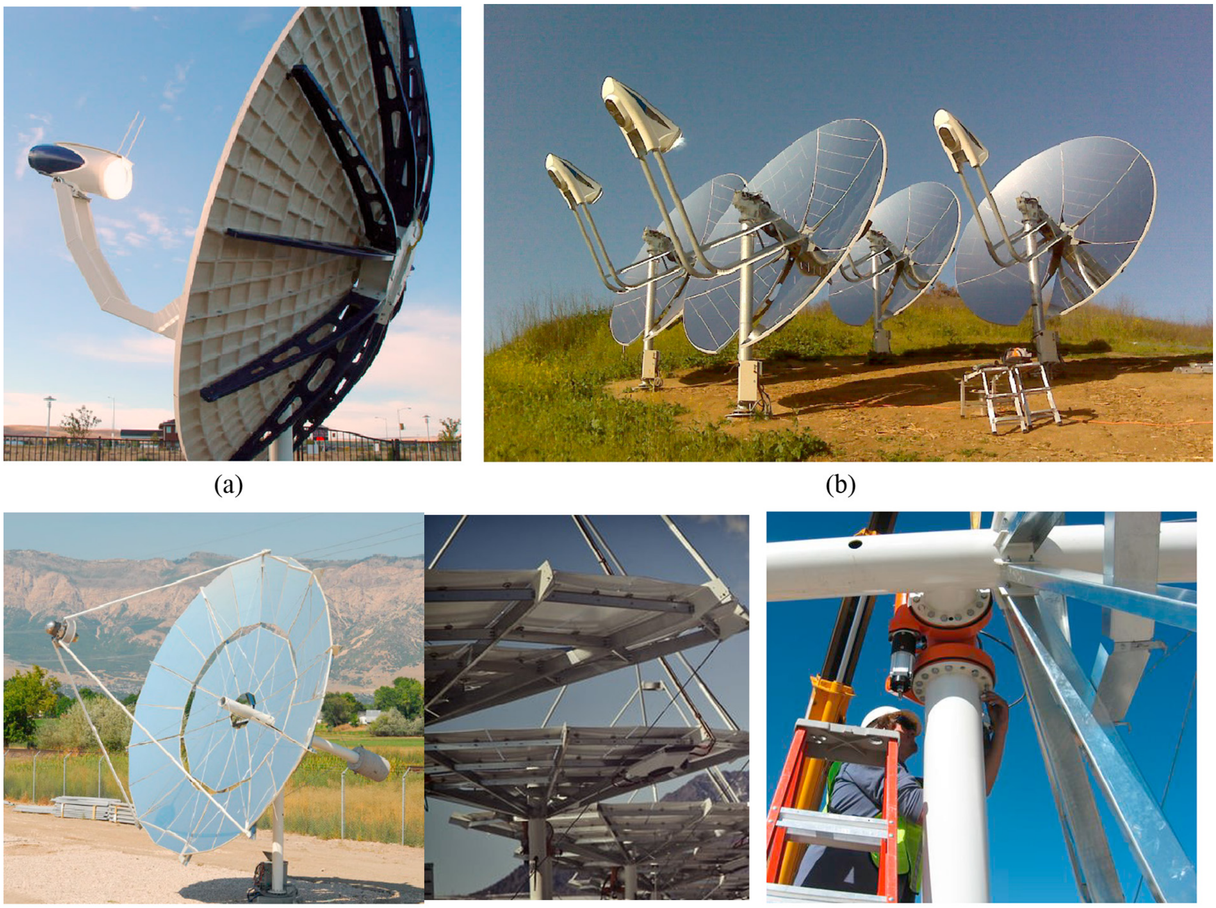

(a) (b) (c) (d) (e)

Fig. 31. Infinia dishes: (a) PowerDish II (SBP, 2017); (b) PowerDish III (SBP, 2017); (c and d) PowerDish IV (Infinia, 2012); and (e) the laterally offset elevation drive of the PowerDish IV (Infinia, 2012).

tion = 0° (at the equinox), and because the dish and receiver have fixed heights, the reflector would require different segments of a paraboloid to achieve an ideal focus as solar declination changes throughout the year. This is not practical, and therefore optical quality is compromised. However, for the 150 °C process heat applications for which Thermax market this dish, the solar concentration is sufficient based on the fixed shape reflector.

5.33. BioStirling-4SKA (BioStirling-4SKA, 2017; Gonvarri Steel Services, 2016; Lindh et al., 2016)

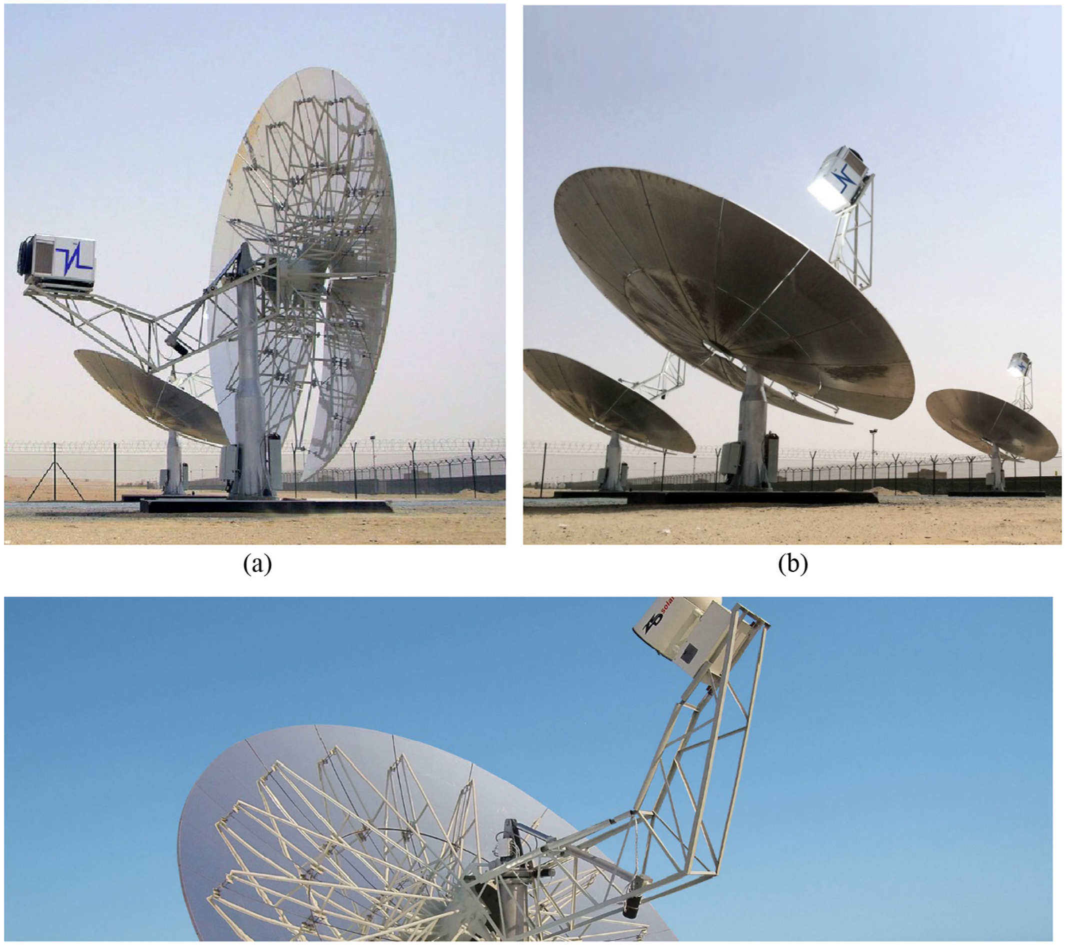
BioStirling is a large European consortium developing a dish-Stirling technology aimed to provide power to the Square Kilometre Array (SKA) project in Portugal. The dish design and fabrication is led by Spanish company, Gonvarri Steel Services. The dish is designed to power a hybrid solar/gas Stirling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

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" (Goldberg, 1980). 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 25 kW USAB 4-95). Once the engine R&D programs were established, for practical and cost-effectiveness reasons, dish size was effectively 'locked in' for the first 5–10 years of the US dish program. Stirling engine availability has continued to dictate dish size since, although other smaller engines (8 kW V160, 3 kW Infinia) have been introduced. Indeed, as Stirling engines were improved and became 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 bigger (e.g. ANU §5.21) and smaller sizes (e.g. Shenandoah §5.4) than were being contemporaneously developed for dish-Stirling applications.

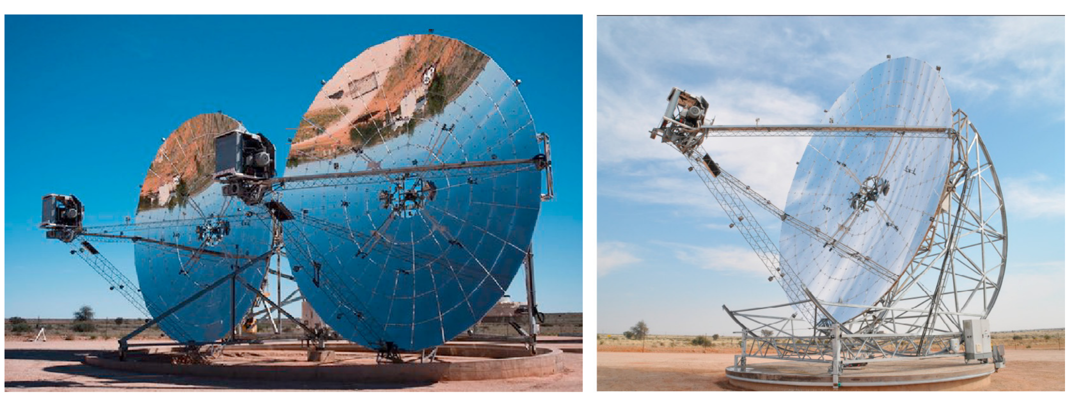
Size has been a topic of great debate for heliostats (Kolb et al., 2007; Coventry and Pye, 2014; Blackmon, 2013), but less so for dishes, probably because of the constraints imposed by Stirling engines. If dish size could be chosen freely, what would be optimal? Lovegrove et al. (2007) analysed cost 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 a 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



(a) (b)

(c)

Fig. 32. (a and b) ZED Solar dishes (with Cleanergy Stirling engines) at the Dubai plant (Cleanergy, 2017), and (c) a ZED Solar dish with a steam receiver (Zed Solar, 2017).



(a) (b)

Fig. 33. Ripasso test site at Upington, South Africa, with (a) dual reflector (The Guardian, 2015) and (b) single reflector prototypes (Ripasso, 2017).

Coventry and Pye (2014) which favour smaller size. It is well known volume manufacturing of engine components is critical to low cost vehicles, and the same is likely to be true for Stirling engines, favouring more numerous, smaller engines and therefore dishes (Fig. 38).

6.2. Tracking style

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

An interesting design conundrum for dishes intended for heavy receivers such as Stirling or Brayton engines, is how to design a balanced, lightweight structure with centre of mass near the elevation pivot, and yet also achieve a suitably uniform flux profile.

(a) (b)

Fig. 34. (a) GOE dishes in Ordos, Inner Mongolia, with Cleanergy Stirling engine receivers (Nilsson et al., 2016), and (b) GOE dish prototypes in Zhang Jiagang, in Jiangsu Province (Great Ocean Energy, 2017).

Fig. 35. The Cleanergy dish in Dubai (Nilsson et al., 2016).

There have been many variations of the MacDonnell Douglass style dish (§5.13), with its slotted reflector to allow pedestal mounting at the centre of mass. To achieve good PCU efficiency and service life, the mirrors must be carefully aligned to compensate for the gap in the reflector. Mirror alignment can be a time-consuming task; however, for most facetted designs it is necessary regardless of whether the dish has a continuous surface or is slotted, and therefore the addition of a slot does not add additional cost with regards to alignment. There are two main alternative designs that have been demonstrated that are balanced, and do not require a slot in the reflector surface. The reflector may be pivoted about its outer edges, for example PDC-1 §5.9 and DISTAL/Eurodish §5.16, or the pedestal mounting may be located behind the reflector, but with addition of a counterweight, for example, the Infinia PowerDish IV §5.27 and ARUN §5.24.

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

Other tracking styles have also been demonstrated, (e.g. polar and declination axes at Shenandoah §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 (Ramaswamy et al., 2002), 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).

Fig. 36. The Thermax SolPac™ D160 dishes (Thermax, 2017).

Fig. 37. The steel structure for the BioStirling dish, without mirrors installed (BioStirling-4SKA, 2017).

(a) (b)

Fig. 38. Infinia Stirling engines in production (ESMAP, 2014).

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 (Abengoa Solar, 2011), Sener heliostat (Lata et al., 2010), than most other dishes. This was done to fit the finished structures onto trucks for delivery of pre-built assemblies.

As noted by Jaffe (1982) 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 (2008) discussed the trade-offs between cost and performance of reflectors used for dish concentrators, and showed that, for high temperature dish-Stirling 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

Table 2
Slope errors reported for a selection of dish concentrators. Slope error values from Andraka (2008) except where additional reference is given.

Dish	Section, Ref.	Facet construction	Slope error (mrad)
Shenandoah	§5.4, Kinoshita (1983)	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, Lopez and Stone (1993)	Stamped steel with thin glass, final shape on a mould	0.6–1.5
WGA/ADDS	§5.18	Sandwich aluminium facets, thin glass	0.8–1.4
DISTAL II	§5.16, Ulmer et al. (2006), Jones (1998)	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
SG4 Big Dish	§5.22	Sandwich construction, thin glass	1.3
Flabeg trough mirrors	Flabeg (2017)	Slumped glass	1.7
Stellio heliostat mirrors	Balz et al. (2016)	Flat glass, curved on support frame	0.9–1.2
Sener heliostat mirrors	Lata et al. (2010)	3 mm glass, on stamped backing	0.94

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 (Andraka et al., 2010). 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 variables 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 (2008) reviewed reported facet slope errors, and data from this review is reproduced in Table 2 along with some additional examples.

Although some of the early dishes had highly accurate but expensive facets (e.g. TBC §5.6, Vanguard §5.12), low-cost fabrication methods were pursued from the earliest days of dish development. For example, General Electric's Shenandoah dish had reflective film adhered to die-stamped aluminium mirrors with rear ribs (Fig. 39). Although optical accuracy targets for this dish were not high, stamping is potentially very cost effective for high volume manufacturing (despite the high cost of initial development due to the dies), and promising optical accuracy has been demonstrated. Stamped mirror panels were employed for the MDAC dish §5.13, and measurements by Sandia indicate <1 mrad slope error, with some as good as 0.6 mrad (Lopez and Stone, 1993). Note that for these mirrors, the final surface shape was given by a mould during the bonding process (not directly from the die stamping), similar to sandwich panels. Stamped constructions have also been used extensively for heliostat mirrors, such as Gemasolar (Lata et al., 2010) with slope error <1 mrad reported.

The highest optical performance has been for sandwich panels, including for dishes such as Sandia 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 mrad. Current commercial suppliers of sandwich mirror panels include ToughTrough and RioGlass Solar. ToughTrough has developed a steel and glass faced, polyurethane cored sandwich panel, which has been used for heliostats (Flabeg, 2013; Procter, 2010) and will be used for the BioSolar-4SKA dish project (§5.33). The specific weight of the mirrors is less than 10 kg/m^2 and the foam core is designed with inhomogeneous density, i.e. the foam density is locally tuned according to structural requirements (Pfahl et al., 2013).

[3] More correctly, the mode of the measured angular error distribution should be determined, per the method recommended by Johnston (1995), but RMS is a simpler proxy for this value.

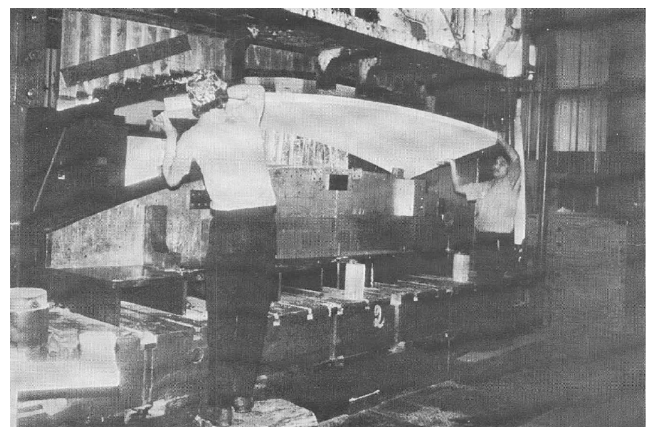


Fig. 39. Die stamping the mirror panels for the Shenandoah dishes (Kinoshita, 1983).

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

Slumped glass mirrors, which are almost standard for parabolic troughs, are rarely used for dishes. Thermally slumped mirrors are heavier, require a more rigid support structure, and historically did not have good enough optical accuracy for dishes. However, optical quality has gradually improved, and one of the major manufacturers Flabeg FE, now claims slope error <1.7 mrad for trough applications (Flabeg, 2017).

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

Finally, it is noted that mirrors for some state-of-the-art heliostats use flat glass, shaped only by the support structure (e.g. Stellio (Balz et al., 2016) and BrightSource). Flat mirrors are supplied with flatness typically <0.3 mrad (Flabeg, 2017), and once shaped can achieve very good RMS slope error values, around 0.9 mrad, or 1.2 mrad across a day in operation in the field (Balz et al., 2016). This design is challenging for dishes, which have significantly smaller radius of curvature compared to most heliostat fields.

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

6.5. Cost reduction opportunities

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

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

These comments are consistent with lessons learnt from more recent dish developments, and the personal experience of the authors. The drive systems, especially azimuth, are a substantial cost. The cost is driven by the need to support a large overturning moment, while maintaining accuracy in tracking. The carousel-style drive approach easily supports the overturning moment, but generally requires more extensive site preparation and foundations, driving in-field labour costs. Several CSP developers (SES for dishes (Terracon Consultants, 2011), BrightSource for heliostats (Huss, 2012) have eliminated concrete pier foundations, and utilised driven or vibrated steel pedestal/foundation drive supports. This significantly swings the cost drivers in favour of a pedestal type support tower, despite the higher gearbox and bearing costs.

Modularity has long been mentioned as an advantage for dishes over larger scales CSP systems (e.g. Acurex (Vindum, 1981)). However, more recently dish systems have been proposed in very large fields to reduce cost by productionisation of the installation and assembly (e.g. SES, Infinia). The design of the dish needs to reflect the deployment model, as different competing features are needed for small and large installations. In all cases, the cost is minimised by minimising in-field labour. However, on-site (centralised) assembly and optical alignment, while more expensive than factory assembly, can offset the significant cost of shipping (partially) pre-assembled systems, especially for large-field installations.

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

7. Storage and hybridisation

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

7.1. Dish mounted storage and hybridisation

In the late-1970s and mid-1980s, JPL suggested coupling phase change materials (PCMs) to Stirling engines for energy storage (JPL, 1978; Stearns, 1986). The concept of combining latent-energy transport and latent-energy storage is attractive because it maximises the exergetic efficiency of the entire system, and matches the isothermal input characteristics of the Stirling cycle engine. Both Infinia and Sandia proposed dish-mounted PCM/Stirling concepts that utilised the mass of the storage material as counterweight to the reflector (Fig. 40) (Andraka, 2012, 2013; White et al., 2013). The Infinia concept used a sodium pool in direct contact with a NaCl/NaF PCM as an intermediary to the heater head of the Stirling engine. This helps overcome limitations with the poor conductivity of the salt. The Sandia concept utilised indirect heat transfer between the PCM and sodium, but used a metallic PCM (CuMgSi) to overcome potential heat transfer issues. CuMgSi was selected as the preferred PCM due to its good conductivity, high heat of melting and acceptable cost. In preliminary testing, corrosion of containment materials at the necessary temperature was a challenge. Unfortunately, both research programs were terminated prior to testing on a dish.

Dish mounted engines and receivers may be hybridised with fossil fuels, typically natural gas. Mendez et al. (2010) present a review of the extensive body of past work with hybrid Stirling engines, which includes both directly illuminated hybrid receivers (ESOR, Sundish, BioDish) and hybrid reflux receivers (HYHPIRE, Sandia/NREL, Infinia). In addition, Cleanergy §5.31 is presently developing a hybrid version of its Sunbox Stirling engine as part of the BioStirling-4SKA project §5.33 (Lindh et al., 2016).

7.2. Central storage and hybridisation

Thermal storage at a central facility may be done using the conventional methods employed for other CSP systems, such as the two-tank system or a single tank thermocline system, with various storage media such as 'solar salt' (60% $NaNO_3$ and 40% KNO_3 by mass) or HitecXL (48% $Ca(NO_3)_2$, 7% $NaNO_3$, and 45% KNO_3 by mass) (Gil et al., 2010). The challenge for dish power plants is the choice of HTF to transport energy from the dish field to the storage system. Synthetic thermal oil can be used for temperatures up to 390 °C. Examples of dish plants using oil as both the HTF and storage medium include the Shenandoah §5.4 and Kuwait §5.7 dishes. Lower temperature systems may use pressurised water for storage, as has been demonstrated with the ARUN dishes

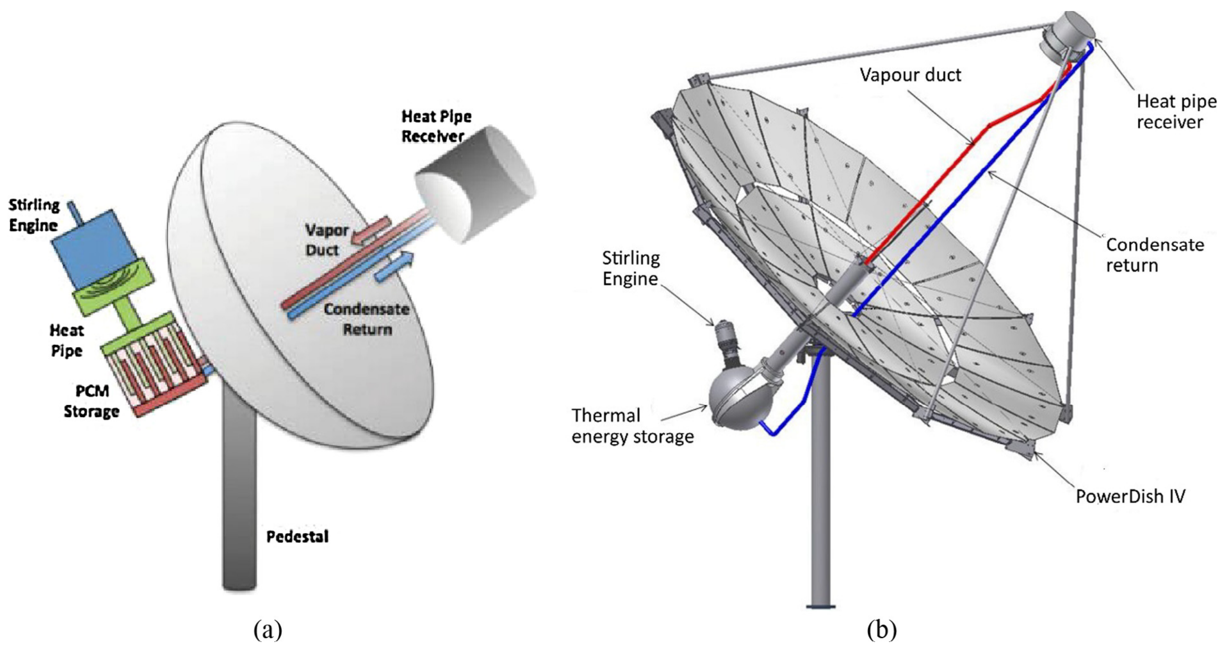


Fig. 40. Dish mounted PCM storage system for the Stirling power cycle as proposed by (a) Sandia (Andraka et al., 2015) and (b) Infinia (White et al., 2013).

§5.24. For temperatures above 390 °C the choice of HTF is more restricted. Solar salt is used as both HTF and storage media in state-of-the-art central receiver plants, and potentially could be used a dish field pipe network. However, the challenge of preventing the salt freezing in an extended pipe network, including through flexible couplings, is daunting. Liquid sodium is an alternative HTF, and with its excellent conductivity and lower melting point may be a better option than solar salt for a dish field. Reticulating pressurised air or other gases is also possible, in combination with a fixed storage bed. This has been demonstrated successfully at the solar tower system in Jülich, which has an air receiver and storage in a ceramic brick bed at 680 °C (Zunft et al., 2011). An integrated storage system with any of these high temperature HTFs - salt, sodium or air - is yet to be demonstrated in a dish field.

There is significant experience with direct steam generation on dishes (§4.3). However, the integration of thermal energy storage (e.g. molten salt storage) with a DSG system is also challenging, due to the 'pinch point' problem, as described by Steinmann et al. (2008). The pinch point is the result of a mismatch in heat transfer properties between the storage medium, with purely sensible heat exchange, and the steam, which undergoes latent heat transfer in both charging and discharging phases. Attempts to resolve the pinch point problem have included use of PCM storage in series with sensible heat storage (Steinmann et al., 2008). Coventry and Pye (2009) proposed two alternative approaches, taking advantage of the more linear temperature-enthalpy characteristics of superheated subcritical steam and supercritical steam to reduce the temperature difference across the steam-salt heat exchanger. A similar approach was proposed by BrightSource (Koretz et al., 2011), where a fraction of the superheated steam was redirected from the power block to a steam-salt heat exchanger to charge the storage while in vapour phase, and then condensed while preheating feedwater returning to the receiver. This storage concept was originally proposed for BrightSource's Ashalim DSG power tower project (now under construction), but the storage component has since been removed (NREL, 2017).

As discussed previously (§4.7) thermochemical storage is another promising option with dishes, but the only concept that has been tested is the ANU ammonia storage concept (Lovegrove et al., 2004).

Peterseim et al. (2013) gave an overview of the many different options for hybridisation of centralised CSP systems. Dishes can be used in series or parallel with an auxiliary source of heat. In a series configuration, dishes may be used to superheat saturated steam, as was demonstrated for a subset of the dishes at LaJet's Solar Plant 1 §5.14, and proposed for HelioFocus' Wuhai plant §5.25. Operation of dishes in parallel with an auxiliary boiler is relatively straightforward from an engineering standpoint, and has been demonstrated at the ANU White Cliffs project §5.11.

8. Outlook

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

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