Taking the ANU Big Dish to commercialization

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Abstract

The ANU 400m^2 "Big Dish" is familiar to most people in the Renewable Energy Community. The first prototype was completed in 1994 and research and development aimed at supporting and improving the technology has continued within the ANU Solar Thermal Group since then.
In 2005, Wizard Power Pty Ltd was established by a Canberra investor in order to take the Big Dish technology to commercial deployment. Wizard Power has a world wide exclusive licence to the Big Dish design and associated patents, the ammonia based thermochemical energy storage system and new advanced mirror panel technology.
In recent times, large scale solar thermal electric power generation technology based on concentrator systems has received increasing attention. New projects have commenced construction in Australia, Europe and the USA.
This paper discusses the prospects for growth of concentrating solar thermal electric technology in general and explores the cost and performance benefits offered by dish systems and the cost optimization that favours sizes of 400m^2 and bigger.

1. INTRODUCTION

In recent years interest in large scale renewable electricity production has grown. The wind turbine industry is the big success story over the last two decades, with growth rates in installed capacity in the range of 20 – 30% per annum. Worldwide installed capacity is now in excess of 35GW$_e$ and annual turnover in excess of US$15billion. Photovoltaics have experienced similar rates of growth but installed capacity is an order of magnitude lower.

Concentrating solar thermal power systems use tracking mirror systems to focus radiation onto receivers that operate at the high temperatures needed for power generation. Most of the world's non renewable electricity generation is produced using steam turbine driven generators. Heat to produce steam comes from coal gas or nuclear sources. Concentrating solar thermal systems have the ability to substitute for these sources and continue to utilize the standard turbine generator technology. Trough concentrators use parabolic trough mirrors to produce a linear focus on a receiver that moves with the trough as it tracks the sun, Linear Fresnel systems use an array of smaller parallel mirrors that track individually onto a fixed linear receiver. Parraboloidal dish concentrators focus to a more concentrated point focus as do heliostat fields focusing to central towers.

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

The ANU has worked on dish concentrator systems since the early 1970's. Early work lead to the construction of the White Cliffs solar thermal station. In 1994, the first "Big Dish" 400m^2 solar concentrator was completed on the ANU campus. In 2005, Wizard Power Pty Ltd was established by a Canberra investor in order to take the Big Dish technology to commercial deployment. Wizard Power has a world wide exclusive licence to the Big Dish design and associated patents, the ammonia based thermochemical energy storage system and new advanced mirror panel technology.

2. THE ANU BIG DISH

The ANU Big Dish design has two working prototypes (as shown in Figure 1), the original prototype installed on the ANU campus (named SG3) and a subsequent similar system provided to the Ben Gurion University in Israel.

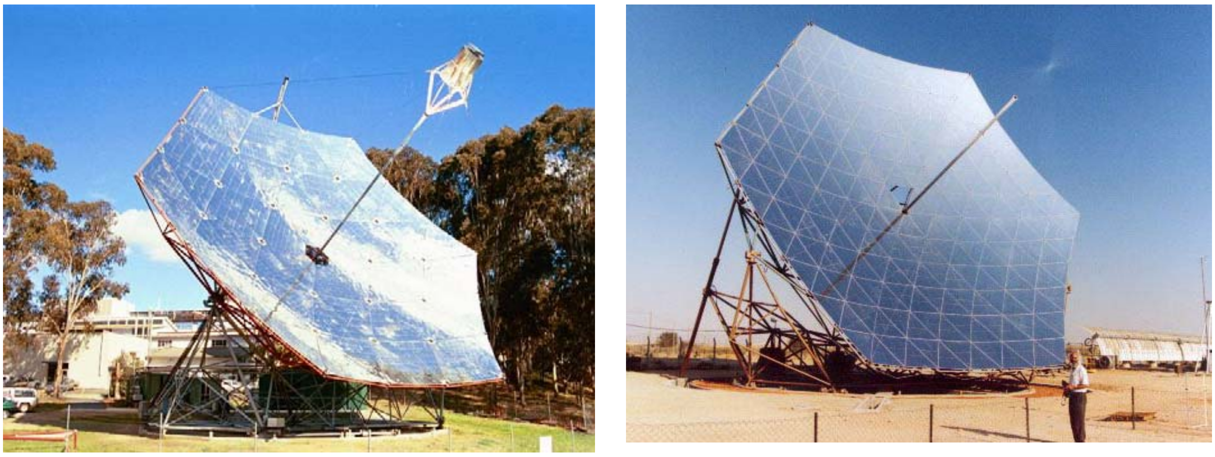

Figure 1 The ANU campus (left) and Ben Gurion University (right) Big Dish prototypes

The structure is based on a space-frame design with a network of tubular steel members joined to spherical nodes. The dishes rotate on reinforced concrete tracks, with a base frame supported by 5 bogie wheel assemblies. Triangular mirror elements are attached to the dish-frame. The mirrors used on the ANU prototype, deliver a peak concentration ratio of 1500 (Johnston 1995).

On the SG3 system a monotube boiler housed in a “top-hat” cross section cavity receiver produces up to 100 g/s of steam that is superheated to typically 500°C at 4.5 MPa. Figure 2 shows the receiver in operation collecting concentrated solar radiation. This steam is passed to the ground via an insulated steam-line and rotary joints. Dish receivers of this nature can provide steam at any temperature and pressure that commercially available steam turbines can work with.

Figure 2. SG3 monotube boiler receiver during operation.

3. INTERNATIONAL PROSPECTS

The success of the wind turbine industry has largely been driven by demand and policy measures in favour of renewable energy in Northern European countries, notably Germany and Denmark. Solar thermal systems are not suited to the prevailing climate in those countries and also, until now, the module size of a large solar thermal power system, of between 20 and $80MW_e$ has possibly been bigger than the market desired. In the last few years this situation has changed. Favourable policies in a range of locations, notably Spain, Italy, California and Nevada are now in operation. Globally the resources needed for renewable energy stations in the 10's of MW_e seem to be increasingly available. Table 1 lists details of current solar thermal power projects under construction around the world.

Table 1. Solar Thermal Power systems under construction around the world as at June 2006.

Project	Location	Initiator	Type	Component suppliers	Status	Design electrical output
PS10	Sevilla (Spain)	Solùcar Energia	Saturated steam CRS	Abengoa	Start of operation 2006	11 MW
Saguaro Power Plant	Red Rock Arizona (USA)	Arizona Power Services	Parabolic Trough with ORC	Solargenix, Schott, Flabeg, Ormat	Start of operation 2006	1 MW
Nevada Solar 1	Nevada (USA)	Solargenix	Parabolic Trough with steam cycle	Solargenix, Schott, Flabeg	Erection started	64 MW
CLFR Liddell	Liddell (Aust)	Solar Heat and Power	Preheating for a coal station; linear Fresnel	Solar Heat and Power	First 1MWth in operation	38 MW
Andasol	Granada (Spain)	Solar Millenium	Parabolic Trough with steam cycle	Schott, Flabeg, Solar Milleniumn	Start of operation 2008 / 2009	2x49.9MW

The most advanced of these is the PS10 central receiver plant in Spain. A recent picture of the heliostat array and the tower under construction is shown in Figure 3. The Solargenix plant in Nevada is the subject of another presentation in these proceedings (Cohen et al 2006) as is the Linear Fresnel System of Solar Heat and Power Pty Ltd (Le Lievre 2006)

Figure 3 The PS10 central receiver solar thermal power plant under construction in Spain, June 2006.

There has been two recent detailed investigations of the long term potential of Solar Thermal Power technology. A study commissioned by the National Renewable Energy laboratory in the US (Sargent and Lundy 2003) and a study for the GEF (2005).

The Sargent and Lundy study is an extremely detailed and high credible study of potential cost improvements for Trough and Tower with Rankine Cycle based power generation. They were exclusively interested in large scale power generation and did not consider dish technology because dish proponents in the US and Europe, have concentrated on small dish / engine systems for remote area power supply only. However, the advantage for dish commercialization efforts is that there is so much technology overlap, that the conclusions of this study can be mapped to dishes relatively easily. The key conclusion of the Sergeant and Lundy study is "that CSP[1] technology is a proven technology for energy production, there is a potential market for CSP technology, and that significant cost reductions are achievable assuming reasonable deployment of CSP technologies occurs."

They have projected market expansion and cost reductions out to 2020 and suggest combined solar thermal power system deployments reaching between 5.4GW_e and 13.6GW_e and Levelised energy costs correspondingly falling to between 3.5 USc/kWh and 6.3 USc/kWh. This is comparable to wind electricity prices.

The Sargent and Lundy study analyses the potential for cost improvement from; technical performance improvements, scale up of plant size and volume production, component by component for both systems. Their aggregated final results predict overall cost reductions will be as shown in Table 2.

Table 2. Cost improvement potential by category.

	Trough	**Tower**
Technical improvements	54%	23%
Scale up	20%	49%
Volume production	26%	28%

To a large extent the relatively lower contributions of scale up and volume production for trough plants, reflect the fact that they are already further developed in these regards than tower systems. Dish systems on the other hand, share an almost identical range of analogous system components at virtually the same level of development as tower systems. It is reasonable to assume a similar breakdown of cost improvements as the Tower case. The world bank study essentially supports all these main conclusions.

4. THE ADVANTAGES OF DISHES

As a baseline representation of the Trough and Tower current state of the art, S&L have used the SEGS VI 30MWe trough system in California and the Proposed Solar Tres 13.65MWe tower plant in Spain. Of all the Californian Trough plants SEGS VI was the most effective implementation of the LS2 trough module. Later plants used an LS3 trough design that actually proved to have some performance issues. The Solar Tres plant is very closely modeled on the proven Solar 2 10MW_e plant also tested in California, however configured to maximize power production rather than experimental investigation.

The details of these current technology plants from the S&L study together with ANU's data on the performance of the Big Dish technology, can be used to make a more detailed comparison. Table 3 aggregates the S&L system performance data for current and trough and tower systems with corresponding figures for current dish systems.

It indicates that annual system performance for a 10MW_e Dish system, would be nearly twice that of a larger 30MW_e trough system and approximately 50% more than that of tower system of the same size.

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[1] CSP stands for Concentrating Solar Power

Table 3. . SEGs VI and Solar Tres data from S&L compared to ANU dish.

	Trough	**Tower**	**Dish**	
System	SEGs VI	SolarTres	Dish now	Dish 10
			ANU	ANU
Size	30MW$_e$	13.65MW$_e$	1MW$_e$	10MW$_e$
Solar Field Optical Efficiency	0.533	0.56	0.85	0.85
Receiver thermal efficiency	0.729	0.783	0.85	0.9
Transient effects			0.92	0.92
Piping loss efficiency	0.961	0.995	0.961	0.961
Storage Efficiency	1	0.983	1	1
Turbine power cycle efficiency	0.35	0.405	0.27	0.35
Electric loss efficiency	0.827	0.864	0.86	0.86
Power plant availability	0.98	0.92	0.94	0.94
Annual Solar to Electric Eff	**10.59%**	**13.81%**	**13.94%**	**19.14%**

The dish optical efficiency is considerably higher than the trough or tower systems because the mirror is always pointed directly at the sun, whereas the trough and tower suffer from a reduction in projected area due to a frequent low angle of incidence (cosine losses). The dish optical efficiency is a product of 93.5% mirror reflectivity, 93.1% average mirror cleanliness and 98% receiver interception. The first two numbers are taken to be the same as used by S&L for the existing trough system. The interception is based on ANU measurements on the SG3 dish.

Receiver thermal efficiency for the dish is based on ANU measurements of losses from receiver prototypes. With a value of 90% considered proven on experimental receivers. The receiver efficiency quoted by S&L for the tower system is an annual average that incorporates losses due to transients from cloud and start-ups. For the trough system, the transient effect is within the averaged turbine cycle efficiency. For the dish the transient effect has been taken out as a separate line, and the value of 92% used is the same as that for a tower system.

Piping loss efficiency for the dish plant has been given the slightly lower value corresponding to a trough plant, on the grounds that the insulated working fluid pipe network will be equivalent. In fact the lower performance trough array will be bigger, with a commensurately bigger pipe network.

No storage is assumed for the initial trough and dish plants
Turbine cycle efficiency is higher for the tower plant than the trough plant because higher steam temperatures are achieved. The lower value of the trough systems has been taken for the 10MW$_e$ dish plant to be conservative, even though the dish system can work at the same higher temperatures of the tower plant. For a smaller 1MW$_e$ dish system, turbine efficiency drops because of the smaller turbine size.

Electric loss efficiency covers the electricity consumption needed for feedwater pumps, actuation systems, cooling tower etc. For the dish the same value as the tower system has been assumed and this is consistent with ANU experience with the SG3 system.

4.1. Optimum size

At 400m^2, the ANU dish is considerably larger than any other solar dishes produced elsewhere in the world. The overall trends by other developers have been to increase size over the years, but 200m^2 is the next biggest to have been built. The ANU Big Dish was to some extent a leap of faith based on the combined experience of group members over the years. Calculating a true optimum size requires consideration of how all the individual cost elements scale with size.
The cost of a dish will be made up of contributions from the various parts of it. Each major component will itself have a fixed cost component and a variable cost component that will have some functional dependence on dish size. At a second order level, both cost contributions will likely be dependant on the number of dishes built in a production run and this will also depend on dish size.

The various components that make up a dish can be placed in three categories:

1. Structural; ie the space-frame, the receiver support, wire stays etc. the material use for structural items would be expected to depend on R^3. The costs will have a fixed component and an R dependant component that is likely to be <= cubic. Ie in straight materials terms, larger orders tend to attract discounts and reduce the per unit mass cost etc.
2. Service; ie hydraulics, receiver, fluid lines, rotary joints etc. The cost of items like this is dominated by manufacturing costs and industry experience suggests that for moderate complexity objects that are not mass produced on an enormous scale, the variable cost component depends on approximately "Capacity"$^{1/2}$, which translates to R^1. Operation and Maintenance costs are also expected to have a large dependence on R^1.
3. Collection; ie the mirrors themselves and mirror related components, If current thinking is followed and each mirror element is an identical mass produced small item, then the mirrors used become virtually independent of dish size and the cost simply depends on area to be covered and hence depends on R^2.

Based on this argument, fitting dish costs to a cubic polynomial in R should be a good approximation.

$$C_{Dish} = F_0 + F_1 \frac{R}{R_{base}} + F_2 \frac{R^2}{R^2{}_{base}} + F_3 \frac{R^3}{R^3{}_{base}}$$

Table 11 shows the best current estimate of the dependence of various components. An estimate of Net Present Value of lifetime O&M has also been added.

Table 4. . Radius dependency of cost contributions for the ANU 400m2 (11m radius) dish..

ITEM	**% Cost**	**Fraction fixed**	**Fraction R depend.**	**Fract R2 dep.**	**Fract R3 dep.**	**Abs. % fixed**	**Abs. %R dep.**	**Abs. %R2 dep.**	**Abs. %R3 dep.**
Foundations	13.20%	0.3	0	0.3	0.4	3.96%	0.00%	3.96%	5.28%
Baseframe	7.17%	0.1	0.2		0.7	0.72%	1.43%	0.00%	5.02%
Centre hub	0.32%	0.3	0.6		0.1	0.10%	0.19%	0.00%	0.03%
Horizontal pivots	0.66%	0.3	0.6		0.1	0.20%	0.40%	0.00%	0.07%
Bogies	1.38%	0.3	0.6		0.1	0.41%	0.83%	0.00%	0.14%
Dish Spaceframe	14.15%	0.1	0.1		0.8	1.41%	1.41%	0.00%	11.32%
Mirror panels	17.35%	0	0	1	0	0.00%	0.00%	17.35%	0.00%
Hydraulic system	9.81%	0.3	0.6		0.1	2.94%	5.88%	0.00%	0.98%
Steam generating receiver	3.96%	0.3	0.5		0.2	1.19%	1.98%	0.00%	0.79%
Rotary joints	1.26%	0.3	0.6		0.1	0.38%	0.76%	0.00%	0.13%
Feedwater and steam lines	2.07%	0.3	0.6		0.1	0.62%	1.24%	0.00%	0.21%
Instrumentation	5.66%	1			0	5.66%	0.00%	0.00%	0.00%
Lifetime O&M @20%	23.01%	0.4	0.4		0.2	9.20%			4.60%
Total per dish	**100.00%**					**26.79%**	**14.13%**	**21.31%**	**28.56%**

There is considerable uncertainty in these allocations of R dependence. Rounding them produces values of 0.33, 0.167, 0.2 and 0.3 for F_0 –F_3.

To a first approximation, the effect of size on thermal performance can be neglected. The generating cost of electricity from a plant will be partly made up of a component that is proportional to the per unit area costs of the dishes. i.e.:

$$\frac{C_{Dish}}{\pi R^2} = \frac{1}{\pi}\left(\frac{F_0}{R^2} + F_1\frac{1}{RR_{base}} + F_2\frac{1}{R^2{}_{base}} + F_3\frac{R}{R^3{}_{base}}\right)$$

The minimum cost will occur when:

$$\frac{d\left(\frac{C_{Dish}}{R^2}\right)}{dR} = -\frac{2F_0}{R^3} - F_1\frac{1}{R^2R_{base}} + F_3\frac{1}{R^3{}_{base}} = 0$$

Which is independent of the R^2 cost dependant term. Figure 4 shows a plot of the per unit area cost function normalized to an 11m radius dish. As well as the estimate corresponding to table 3, a range of different fractional dependencies on R^3 are shown.

A number of observations can be made. The cost curves drop rapidly as R is increased until a minimum is reached and rises quite slowly after that. Based on the current understanding of R dependence, the optimum dish radius is 15m compared to the present value of 11m. The position of the optimum is very sensitive to the nature of dish cost dependence on R, with a high dependence on R^3 favouring a smaller dish. Using the current basic ANU dish design, the extremes of plausible R^3 dependence indicate an optimum between 7 and 20m. Whatever the optimum ultimately proves to be, building 11m radius dishes should result in costs per unit area which are within 10% of the minimum.

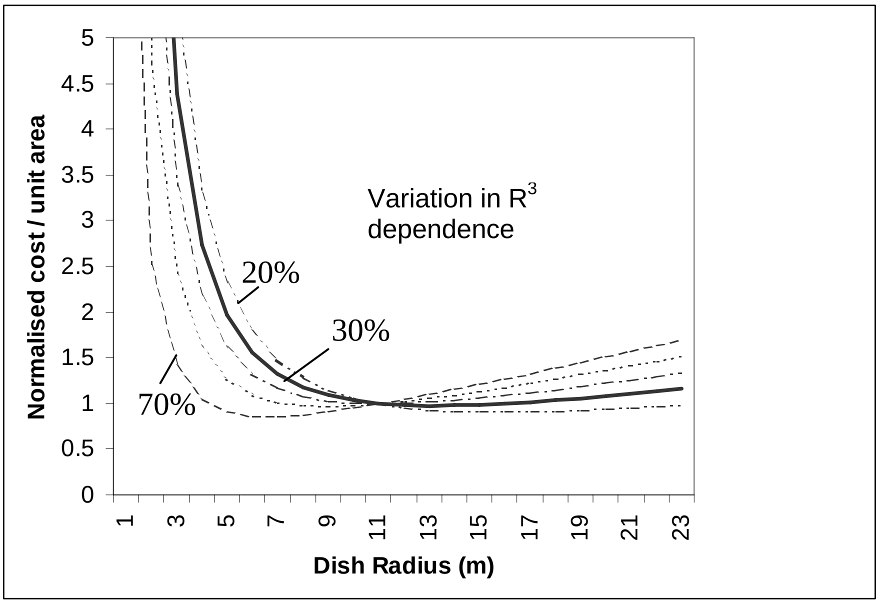

Figure 4. Normalised per unit dish area cost as a function of dish radius, for a range of fractional dependencies on R3. Fixed costs and R1 dependant fractions are kept in the ratio 2:1. and R2 costs kept at 20%.

5. WIZARD POWER’S PLANS FOR COMMERCIALISATION

Wizard Power Pty Ltd, (see www.wizardpower.com.au) is a sister company of Wizard Information Services. Wizard Information Services designs and delivers comprehensive Information Technology solutions, employs more than 200 skilled personnel and exports to Asia, Europe and North America. Apart from the financial linkages, Wizard Power benefits from its sister company’s committment to systems design and integration of complete solutions.

Wizard Power’s goal is to develop solar thermal base-load and peak power storage & generation systems ranging from the 10’s of MW to ultimately the GW scale. The portfolio of IP licenced from the ANU, includes the ammonia based thermochemical energy storage system that has been investigated for many years (Lovegrove et al 2003). Integrated thermal energy storage is one of the key competitive advantages of the solar thermal power systems. By storing energy by the thermochemical approach, many of the components substitute for components that are needed for a direct steam generating system in any case. In addition, the power block can work with a higher capacity factor that it otherwise would and hence improves its economic performance. Overall the result is storage of energy for dispatchability at close to 100% effective efficiency and with relatively small extra cost.

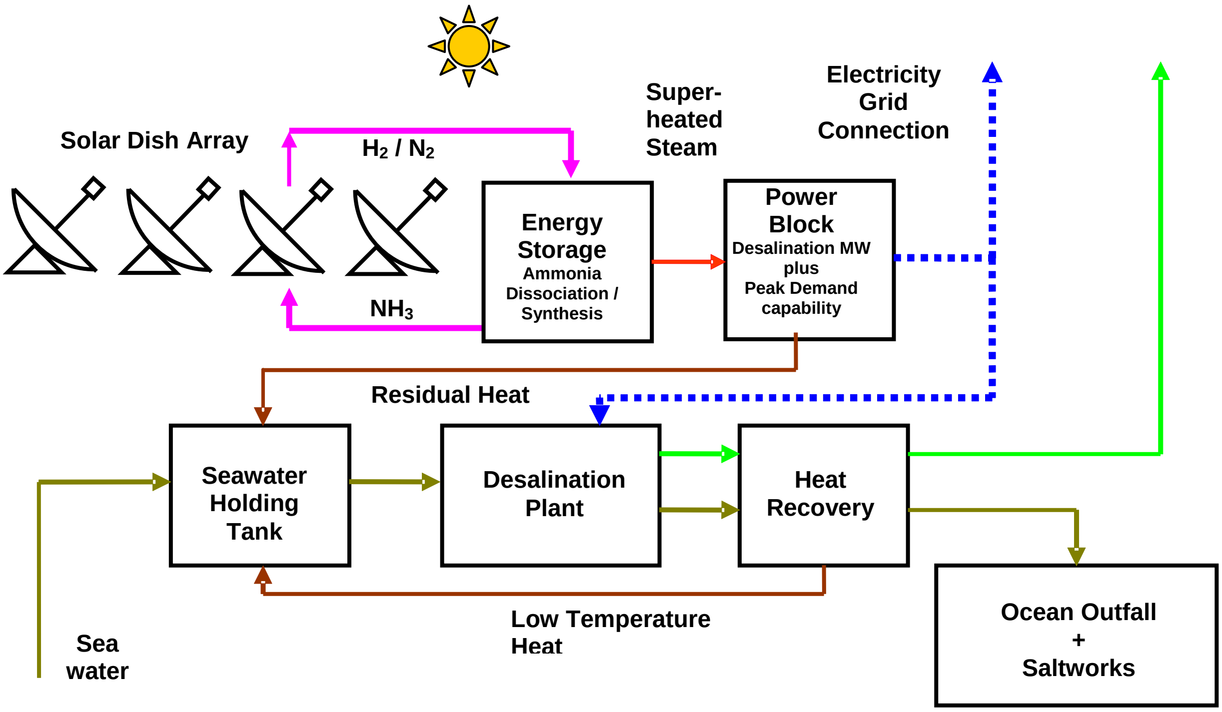

Figure 5. Conceptual design of a combined dish based solar thermal desalination and power station.

The large amount of low temperature heat that is produced as a byproduct of thermal power generation, motivates investigation of integrated solutions that also use this energy stream. The current focus of this approach is combined desalination and power generation. Possible desalination technologies for this purpose have been reviewed in Burgess and Lovegrove (2005). Reverse Osmosis technology is favoured on economic performance grounds and this technology benefits from the application of the low temperature heat. Figure 5 Illustrates the arrangement of such a combined system.

Looking further into the future, renewable transport fuels are an area of obvious strategic importance. Wizard Power has identified solar thermochemical gasification of hydrocarbons such as biomass or coal as a competitive route to this end. A paper reviewing possible approaches to this is also presented in this proceedings (Munzinger and Lovegrove 2006).

In the short term, current efforts are focused on the design of a “Generation II Big Dish” and the completion of a prototype byt the end of 2007. This effort is being supported by a $3.5m grant from the AusIndustry REDI program.

The improved dish will be optimized for cost reduction and manufacturability. A key component area in this regard is the mirror panels. After 12 years of operation, the mirrors on the SG3 dish are in a very poor state. They were in any case not a design that is amenable to mass production. Wizard Power’s portfolio of licenced IP includes ANU’s Glass on Metal Laminate based mirror panels. These offer, higher optical performance, durability and ease of mass production.

Following completion of the new dish prototype, a small scale power system of between 10 and 20 dishes with steam turbine power generation is expected. Although a number of potential sites have been suggested for this, specific plans are still being developed.

6. CONCLUSIONS

After many years of little or no growth, concentrating solar thermal power technologies are now experiencing a resurgence, with approximately 200MWe total plant capacity under construction in June 2006. Studies show that solar thermal power technologies have considerable scope for growth and that electricity costs are projected to fall to similar levels as those of large scale wind systems. Comparison on an equivalent basis of Dish, Trough and Tower systems, with Rankine cycle power generation at the 10MWe level, indicates that dishes have solar to electric conversion efficiencies 50% higher than tower plants and 100% higher than troughs. This strongly suggests that they will perform well economically.

After many years of development work at ANU, the Big Dish technology, ammonia based thermochemical energy storage and advanced mirrors have been licenced exclusively to the new start-up company Wizard Power Pty Ltd. Wizard Power is working with ANU to produce a Generation II dish prototype and expects to follow that with a multiple dish demonstration power plant in the near future.

7. REFERENCES

Le Lievre P. 2006."Design of 6.5 MW solar thermal electricity plant with zero fossil fuel backup" Proceedings of Solar 2006, ANZSES annual conference, Canberra, Australia, 13 -15 September 2006.

Lovegrove K. A. Luzzi, I. Soldiani and H. Kreetz “Developing Ammonia Based Thermochemical Energy Storage for Dish Power Plants.” Solar Energy, 76 pp 331 – 337, 2003.

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

GEF 2005. “Assessment of the World Bank / GEF strategy for the market development of solar thermal power” Global Environment Facility, World Bank, 2005

Cohen J et al 2006. Presentation on behalf of Solargenix, Proceedings of Solar 2006, ANZSES annual conference, Canberra, Australia, 13 -15 September 2006.

Munzinger M. and Lovegrove K. “Biomass Gasification using Solar Thermal Energy”. Proceedings of Solar 2006, ANZSES annual conference, Canberra, Australia, 13 -15 September 2006.

Burgess G and Lovegrove K. “Solar thermal powered desalination: membrane versus distillation technologies”. Proceedings of Solar 2005, ANZSES annual conference, Dunedin, New Zealand, November 2005.