Presented at Solar World Congress, Beijing, September 18 – 22 2007

PARABOLOIDAL DISH SOLAR CONCENTRATORS FOR MULTI-MEGAWATT POWER GENERATION

Keith Lovegrove
Department of Engineering,
Australian National University,
Canberra ACT 0200
,AUSTRALIA
keith.lovegrove@anu.edu.au

A Zawadski and J Coventy
Wizard Power Pty Ltd
Barry Drive
Canberra ACT
AUSTRALIA

ABSTRACT

Large scale solar thermal electric power generation technology based on concentrator systems are recieving increasing attention, with a range of large systems around the world recently completed or under construction. The first prototype of The ANU 400m^2 "Big Dish" solar concentrator was completed in 1994 and research and development aimed at supporting and improving the technology has continued since then. In 2005, Wizard Power Pty Ltd was established to take the Big Dish technology to commercial deployment. The ANU is currently working with Wizard Power on the design for a second generation prototype that is due for completion by the end of 2007. This new design will be optimized for cost effective mass production. Plans are under way to follow this with a first power station implementation incorporating ammonia based thermochemical energy storage.

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 Power systems via trough systems, have a strong track record, with 354MW$_e$ of installed capacity in California, operating continuously for 20 years. After a long period of inactivity, the last two years have seen a upsurge of new projects under construction.

Concentrating Solar 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. Paraboloidal dish concentrators focus to a more concentrated point focus as do heliostat fields focusing to central towers.

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 (shown in Figure 1) 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.

Figure 1 The ANU campus Big Dish prototype

2. THE ANU 400m^2 DISH SOLAR CONCENTRATOR

The ANU Big Dish design has two working prototypes, the original prototype installed on the ANU campus, [1] and a subsequent similar system provided to the Ben Gurion University in Israel.

The structure is based on a space-frame design. Altitude / Azimuth tracking operation is used, with the dishes rotating on reinforced concrete tracks, with a base frame supported by wheel assemblies. The ANU prototype, delivers a peak concentration ratio of 1500 [2].

On the ANU campus dish, a monotube boiler housed in a "top-hat" cross section cavity receiver produces steam that is superheated at up to 500°C at 4.5 MPa. 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.

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 high solar resource locations, notably Spain, Italy, California and Nevada are now in operation. Globally the financial resources needed for renewable energy stations in the 10's of MW_e seem to be increasingly available.

The 11MW_e PS10 central receiver plant was commissioned in Spain early in March 2007 and the Nevada Solar 1 system, a 64MW_e trough concentrator based system was brought on line by Accionna Solar in June 2007. A range of other plants are under construction or planned, including in Australia, the Compact Linear Fresnel System of Solar Heat and Power Pty Ltd [3].

There have 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 by Sargent and Lundy [4] and a study for the World Bank [5].

The Sargent and Lundy study is a detailed and credible study of potential cost improvements for Trough and Tower systems with Rankine Cycle based power generation. 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 as a result of technical improvements, scale up and volume production. This is comparable to wind electricity prices. The World Bank study essentially supports all these main conclusions.

4. THE ADVANTAGES OF DISHES

Sargent and Lundy have used the SEGS VI 30MW_e trough system in California and the Proposed Solar Tres 13.65MW_e tower plant in Spain as a baseline. 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 Sargent and Lundy study together with ANU's data on the performance of the Big Dish technology, can be used to make a more detailed comparison of performance. Table 1 aggregates the Sargent and Lundy 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.

The dish optical efficiency is considerably higher than that of 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 Sargent and Lundy for the existing trough system. The interception is based on ANU measurements on the SG3 dish.

TABLE 1. . SEGs VI and Solar Tres data from Sargent and Lundy compared to ANU dish.

	Trough	**Tower**	**Dish**	
System	SEGs VI	SolarTres	ANU / Wizard Pwr	
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%**

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 Sargent and Lundy 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.

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 feed-water 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. Calculating an 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. To a good approximation the dependence of cost on dish radius (R) can be fitted to a cubic polynomial. Mirror panels contribute a large amount of the R^2 dependence and the R^3 dependence is linked to the structure itself. Other key items contribute to fixed costs and costs that grow linearly with size. Data from the existing dish systems has been analysed to produce the solid curve in Figure 2. The other curves explore a range of dependencies on R^3.

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 SG3 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.

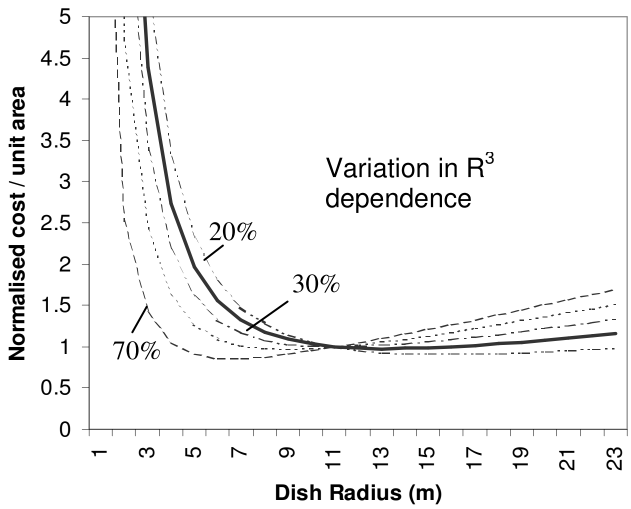

Figure 2. Normalised per unit dish area cost as a function of dish radius, for a range of fractional dependencies on R^3. Fixed costs and R^1 dependant fractions are kept in the ratio 2:1. and R^2 costs kept at 20%.

5.CONTINUING DEVELOPMENT OF THE TECHNOLOGY

Wizard Power Pty Ltd, (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 commitment 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 [6]. 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.

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.. Reverse

Osmosis technology is favoured on economic performance grounds and this technology can also benefit from the application of the low temperature heat.

Looking further into the future, renewable transport fuels are an area of obvious strategic importance. Wizard Power has identified solar thermo-chemical gasification of hydrocarbons such as biomass or coal as a competitive route to this end. ANU is investigating gasification using supercritical steam for this purpose [7].

In the short term, current efforts are focused on the design of a "Generation II Big Dish" and the completion of a prototype during the first half of 2008. This effort is being supported by a AUD3.5m grant from the Australian Federal Government's "Renewable Energy Development Initiative" program.

The improved dish will be optimized for cost reduction and manufacturability. A key component area in this regard is the mirror panels. They will employ ANU's Glass on Metal Laminate based mirror panels. Previous work [8] has identified that identical panels with a fixed average radius of curvature can be used to give acceptable optical performance, thus facilitating mass production. Square panels with a linear dimension of approximately 1.2m are anticipated and overall aperture area will rise to approximately $500m^2$.

Plans are also underway for a first power station that will also incorporate the ammonia based thermo-chemical energy storage technology. This project is also supported to the level of AUD7.4m from the Australian Federal Government's "Advanced Energy Storage Technology" program.AUD14m project. At least 4 large dishes will be included.

6. CONCLUSIONS

After many years of little or no growth, concentrating solar thermal power technologies are now experiencing a resurgence. 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 potential 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

(1) CADDET (1999). "Solar thermal demonstration system with a large paraboloidal dish concentrator". Technical Brochure No. 105, www.caddet-re.org.

(2) Johnston G. "Flux mapping the 400 m^2 "Big-Dish" at the Australian National University", ASME Journal of Solar Energy Engineering, Vol. 117, pp 290-292, 1995.

(3) Mills, D.R., Le Lièvre, P., Morrison, G. and Millioud, A. "Compact linear Fresnel reflector progress." Proceedings of the 13th International Symposium on Concentrating Solar Power and Chemical Energy Technologies, 20 June 2006, Seville, Spain, ISBN 84-7834-519-1.

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

(5) GEF 2005. "Assessment of the World Bank / GEF strategy for the market development of solar thermal power" Global Environment Facility, World Bank, 2005

(6) Lovegrove K,. Luzzi A. and Kreetz H. "A solar driven ammonia based thermochemical energy storage system." Solar Energy, Vol 67, Nos 4-6 pp 309-316, 1999.

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

(8) G Johnston, K Lovegrove and A Luzzi, "Optical performance of spherical reflecting elements for use with paraboloidal dish concentrators". Solar Energy vol 74 pp 133 –140, 2003.