Design of a 240 MW_e Solar Thermal Power Plant

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In this paper, the general design philosophy for a large 240 MW_e pure solar storage plant is discussed. The proposed stand alone plant design will use the same low cost Compact Linear Fresnel Reflector (CLFR) array system previously reported (Mills et al, 2003; Hu et al, 2003) and currently being constructed for a coal fired plant preheating project. In the stand-alone solar plant, the costs of hybrisation with fossil fuel are found to be high, and lower temperature operation seems more cost-effective. The advantage gained by low temperature operation derives from an unusual combination of large low cost low temperature turbines developed for the nuclear industry, and an inexpensive storage concept which suits that particular temperature range. Should both options be applicable, then this may be the most cost-effective solar thermal electricity development path. Comparison of solar electricity cost against a typical 400 MWe coal fired plant in the USA suggests similar cost/performance without green incentives.

Introduction

There has been much emphasis placed in the past on the adaptation of high temperature fossil fuel turbines to solar energy, with an attendant ability to utilise fossil fuel for backup energy. However, there has been a recent shift of interest to 100% solar plants because of the strict incentives that have been set up in countries like Spain, and Germany. Fully renewable operation is also advantageous in tradeable renewables certificates programmes like that of Australia, because the investment in the power block can be repaid at a higher rate.

In the past, it has been usually presumed that primary fossil fuel in large quantities is cheaper than solar heat. We think of solar energy as expensive. Perhaps we should be thinking that the handling of fossil fuel is also expensive. Recent results of a tender in Cyprus for a 120 MW oil fired fossil fuel plant were Turbines: 42.7%; Boilers: 31.6%; Flue Gas Desulpherisation: 14.1%; Transformers: 11.6%. Boilers and fossil fuel treatment are about 45% of the cost. The cost of 20 years of oil is very similar to the avoided fossil fuel equipment. Perhaps 2/3 of the lifecycle cost of this plant is directly related to either fossil fuel handling or fossil fuel price.

Hybridisation with fossil fuel is used to give solar more reliability in the absence of storage. However, the price paid by a solar system for hybridisation is high, because the solar system must be made compatible in output temperature with the fossil fuel system, and because the actual cost of equipment to handle, combust and dispose of fossil fuel waste is also surprisingly high. A turbine system and storage unit optimally designed for pure solar heat may be very different from that which is designed for a solar/fossil hybrid.

Low cost solar array design

In this paper, the general design philosophy for a large pure solar storage plant is discussed. The proposed stand alone plant design will use the same low cost Compact Linear Fresnel Reflector (CLFR) array system previously reported (Mills et al, 2003; Hu et al, 2003) as is being constructed for a coal fired plant preheating project of 35 MWe integrated with a coal-fired plant. This current coal saver project has been now been re-estimated to be 40 MW_e. The project, being built for Macquarie Generation, is composed of three stages; a proving array of 1100 m^2, an intermediate array of 20236 m^2, and a final array of 134909 m^2. After stage 3 is built, it will be the largest solar electricity plant built since the last LS3 parabolic trough field built in California in 1990, and will provide a solar electricity capacity about 3 times the current PV capacity of Australia. The kWh cost of the first plant is expected to be similar to, or below, current wind technology in Australia.

Fig. 1. The Stage 1 array and tower line produced by SHP at the Liddell power plant site.

The array system is linear like a parabolic trough collector, but it has many advantages over troughs which allow significant cost reductions, such as a long focal length with allows elastically bent flat standard glass reflector to be used.

The array technology used in this project is of the Linear Fresnel type and was originally developed at the University of Sydney (Mills and Morrison,1999). It is called the Compact Linear Fresnel Reflector (CLFR) technology. In this approach, ground level reflector rows aim solar beam radiation at a downward facing receiver mounted on multiple elevated parallel tower lines. The technology is innovative in that it allows reflectors to have choice of two receivers so that a configuration can be chosen which offers minimal mutual blocking of adjacent reflectors and minimum ground usage. However, there are also many supporting engineering innovations in the commercial product, including highly rigid space frame mirror supports with 360° roatation capability, long horizontal direct steam generation cavity receivers, and array fine tracking control electronics. The design of the CLFR array design incorporates high volume production elements to reduce engineering cost.

The authors have previously described some of the cost advantages of the CLFR array system (Mills et al, 2003) of the current trough technology, but have not discussed the general issue of overall stand-alone solar plant design. The traditional approach to the design of a line focus solar plant is to use a parabolic trough system to the supply of heat at between 320°C and 400°C to the main boiler and superheater of a conventional turbogenerator (NREL, 2003). Some higher cost trough designs utilise fossil fuel in off-solar hours, not only to increase the plant capacity factor, but to lower the overall cost of delivered energy. The present CLFR design can also be straightforwardly adapted in this direction. However, in trough and CLFR systems, thermal losses can rise rapidly with array operating temperature, partially cancelling out improvements in thermal conversion efficiency. In addition, the traditional path of using a superheated turbine requires more highly efficient and durable selective coatings, thicker-walled tubing for steam pressure containment, and the use of oil instead of water as a heat transfer fluid if operating above the water triple point.

A 240 MW non-fossil power block

An alternative case can be made for a design which minimises array thermal losses using low temperature (200°C – 300°C) saturated steam Rankine cycle turbines. Although some effort has been made to look at low temperature trough systems using small organic rankine cycle turbines (NREL, 2002), in this temperature range, higher efficiency demands a large turbine. The array cost of the CLFR is low enough that the added cost of fossil hybridisation is relatively high. For low cost and reliability, one needs a proven system stripped of expensive fossil fuel equipment.

Such systems exist. The nuclear power industry has spent many years and huge sums developing non-fossil fuel turbines which, at about 31-33%, are more efficient than smaller organic rankine cycle plants. These turbines operate from wet steam, using steam separators to dry out the steam before entering the turbine, and they use special turbine blade design. No superheating stage is required, so the solar array needs only meet the main boiler operating temperature, which in the case of the VVET is only 250°C. If one were to design a turbine type to to suit a large solar direct steam generation array like the CLFR, it would be something close to the VVER design, although there might be a case for operating in the range 300°C – 350°C to increase thermodynamic efficiency. Operation at 250°C allows significantly lower array losses than operation at 450-500°C as proposed for advanced trough systems (NREL, 2003) and allows the use of a wider variety of air stable selective coatings on the receiver. Steam pipes are also substantially cheaper at the lower temperature range.

However, the smallest nuclear turbines one can obtain are of about 240 MW_e peak capacity, which would lead to a solar plant larger than any yet built. The low temperature turbine costs used in the paper are based upon approximate estimates (VVER, 2003) supplied by JSC "Atomstroyexport" (Russia). The supply of a 240 MWe

VVER steam turbine and steam separator and control equipment of about US$18 million for a single turbine, well below high temperature turbine cost. It is conservatively assumed in this paper that an additional 1/3 will be added to the turbogenerator price to cover delivery and installation. Several sites have been found in Australia with excellent solar radiation and grid access. The most attractive of these has enough spare grid capacity for a 240 MW_e installation.

A low temperature low cost storage system

The proposed plant uses the concept of Underground Thermal Energy Storage (UTES), which we will refer to in this paper as 'cavern storage'. Pressurised water cavern storage appears to have been first proposed by R&D Associates in 1977, but the original reference is no longer available. The oldest extant major analysis is a 1983 report (Copeland and Ullman, 1983; Dubberly et al, 1983) from the Solar Energy Research Institute SERI (which later became NREL). The SERI report was a study of different storage options prepared for the U.S. Department of Energy (DOE) in the early 1980's. Cavern storage involves storage of water under pressure in deep metal lined caverns where the pressure is contained by the rock and the overburden weight. There are no heat exchangers, and a low cost makeup water tank is provided on the surface. The array supplies steam to the cavern water, and steam is flashed directly from the cavern into the turbine, in a very similar manner as steam is evaporated from a nuclear boiler vessel into a nuclear turbine. Fourteen organizations were involved in deriving the comparative rankings, which indicated quite definitively that UTES for a large system was the cheapest storage method.

Because costs have changed greatly in some areas, Tanner (2003) has produced, at the suggestion of one of the authors, an engineering thesis report on cavern storage applied to the case of the CLFR. This study investigates, using estimates supplied by experienced engineering and excavation companies, the current costs of a steel lined caverns at depths of 200m and 400m using modern excavation techniques. This report indicates that cavern storage is now much cheaper than other currently proposed storage methods at installed costs under US$3 per kWh_t. This report is being rewritten for publication. With low cost storage, there is a tendency for total system delivered electricity costs to be reduced as the capacity factor increases.

Comparison against coal technology

In a recent U.S. regional power plan discussion document (North West Council, 2002) the cost of a 400 MW_e pulverised coal plant was found to be $1468/$kW_e$ in the North West USA. This plant is used as a coal cost baseline for comparison costings against two CLFR/cavern scenarios, one with 54% capacity factor and one with 68%. In Table 1, the coal plant is given an 80% capacity factor, within the normal range for capacity factors in the USA. David and Herzog (2003), for example, use 75% in a study of carbon sequestration. The coal plant IRR was held to 14%, assumed as a reasonable payback for solar plants in NREL (2003), by adjusting the wholesale price for electricity. premium charged for peaking sales, because as the capacity factor is reduced, there is a greater opportunity to indulge in 'peak lopping', giving a higher return per kWh_e. The IRR for such trading can only be determined using a complex grid pricing model not available to the authors.

Table 1. Costs and IRR of coal and CLFR systems

2nd Year Example Revenue Sheet	400 MWe Coal	CLFR/Cavern	CLFR/Cavern
Capacity Factor	0.80	0.54	0.68
Electricity Sale $/MWH	45.23	45.23	45.23
Environmental Support $/MWH		0.00	0.00
Total Revenue $ per MWh	**45.23**	**45.23**	**45.23**
Collector Area m^2	0	3,188,571	3,985,714
Array related cost $/kWe	0	1435	1744
Storage Cost $/kWe	0	68	92
Power block and BOP cost $/kWe	1468	281	281
Total Cost $ per kWe	**1468**	**1784**	**2117**
Annual Output MW(th)	14,038,462	3,620,800	4,526,000
Thermal to Electrical efficiency	39.0%	31.5%	31.5%
Online Status	0.98	0.98	0.98
Total Annual Equivalent MWH Output	2,522,880	1,117,741	1,397,176
Annual Gross Plant Revenue US$	**111,315,773**	**45,291,605**	**56,614,506**
Coal cost 0.71 MMBTU	42,522,644	-	-
Reflector Array Cleaning	-	3,587,143	4,483,929
Operations and Maintenance	15,646,080	2,022,019	3,159,404
Debt Payment	28,146,027	20,522,963	24,359,041
Annual Gross Costs of Service US$	**58,168,724**	**26,132,125**	**32,002,373**
Annual Net Plant Revenue US$	**53,147,049**	**19,159,481**	**24,612,133**
Net Present Revenue per MWh	$43.05	$43.05	$43.05
Net present cost per MWh	-$28.97	-$24.43	-$23.84
Net present profit per MWh	$14.07	$18.61	$19.21
CPI	2.5%	2.5%	2.5%
Debt cost	7.2%	7.2%	7.2%
Debt ratio	50%	50%	50%
25YR IRR	**14.00%**	**13.87%**	**14.76%**

The solar plants were then evaluated on this selling price and it was found that their IRR is comparable to coal; slightly higher than coal for the 68% capacity factor plant and slightly lower for the 54% plant. The optimal capacity factor depends upon the pricing for electricity at different times of day and year.

In Fig. 2, the capacity factor of new pulverized coal plant is now varied to produce a range of electricity wholesale prices which meet the desired IRR of 14%. This is compared to the 68% CF CLFR/cavern storage solar plant which is also held to an IRR of 14%. The graph shows that the coal fired plant is more costly up to about a CF of

82%, and even at a CF of 90% is only \$5 per MWh_e less expensive than the 68% CF solar plant. This suggests that minimal measures such as low priced carbon trading would be sufficient to provide solar competitiveness against the cheapest baselaod coal fired plant.

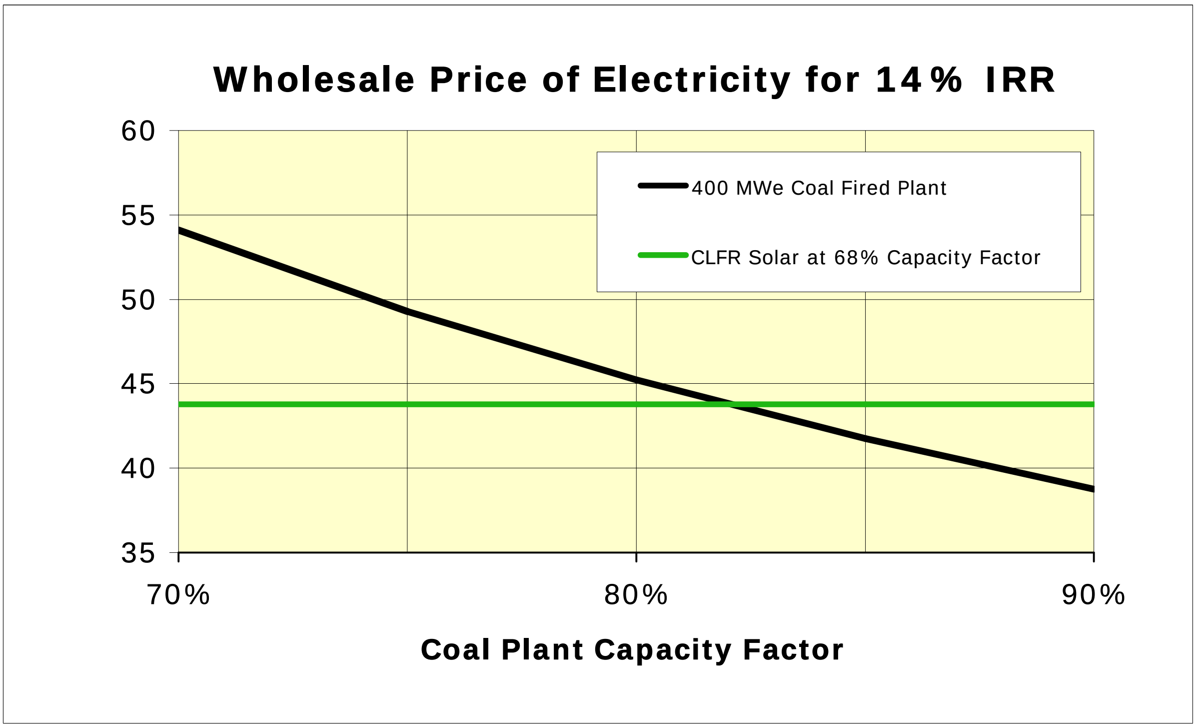

Fig. 2. Cost of electricity in the second project year required to produce a 14% IRR in high CF Coal and Solar scenarios. The Coal CF is allowed to vary while the CLFR storage plant is held at a 68% CF, close to the higher range of solar CFs possible using daily storage in mid-latitudes such as NSW and California.

Comparison against advanced trough and tower technology

The CLFR/cavern 2010 proposal of 54% CF at US\$1784 per kW_e, offers costs well below 2020 estimates for both troughs at 56% CF (2225 – 3220 \$/kW_e) contained in a NREL report (NREL, 2003) which use Hitec salt storage at up to 500°C. The CLFR/cavern proposals at 68% and 81% offer costs (2118 and 2486 \$/kW_e) much below 2018 'base case' solar tower plants at 73% (3591 \$/kW_e) and comparable to the revised Sunlab reference case of \$2340 for the year 2018. It should be mentioned that the CLFR/cavern 2010 proposal is far from optimised; Tanner (2003) suggests cavern storage at 350°C would be cheaper, and a US nuclear turbines or modern Kalina cycle turbine operating at close to 300°C would offer a 10% efficiency increase, but this would have to be compared against turbine cost.

Conclusions

The potential cost advantage gained by low temperature operation derives from an unusual combination of large low cost low temperature turbines developed for the nuclear industry, and an inexpensive storage concept which suits that particular temperature range. Should both options be applicable, then this is likely to be the most cost-effective and simple solar thermal electricity development path, using simple solar collector technology already being installed, and a proven turbine from the nuclear industry.

Cavern storage cannot be taken higher than about 360°C and still has some developmental uncertainty ahead of it, but two reports have now identified it as potentially the lowest cost storage concept. Recent discussions that the authors have had with geologists and mining companies suggest the concept is in the realm of current mining technology and can be widely applied; suitable rock structures are common. If suitable geological structures are not available, Caloria oil storage with a CLFR array is a low risk option available for a cost which is still below the trough collector systems. Environmentally, however, cavern storage would be safer than either molten salt or oil solutions.

The electricity wholesale cost for the unoptimised CLFR/cavern in 2010 (the earliest that one can be finished is about 2009) at 68% capacity factor, without the use of any Green support mechanisms, is comparable to the cost of some current conventional pulverised coal-fired (PC) generation in the USA. The cost advantage of coal appears at high capacity factor, but even at a coal CF of 90%, the advantage is only about US$5 per MWh_e.

The CLFR/cavern approach is unoptimised and may benefit from slightly higher operational temperatures should a suitable turbine be available. Such turbines may be available in the USA or Europe. The coal fired plant referenced also has a larger turbine than the solar 240 MW_e. According to NREL, 2003, a 400 MW_e power block should be 25% cheaper per kWh delivered than a 240 MW_e equivalent, which reduces cost by about US$3 per MWh_e. Furthermore, David and Herzog (2003) suggest that pulverised coal plants could incur an additional cost of US$30 per MWh_e for long term cost carbon sequestration.

This brief discussion needs extensive elaboration and more detailed work within the scope of a real project structure. The authors have begun site investigations for a 240 MW_e plant of the type described, assisted by Australia's largest utility.

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