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Assessment of Solar-Coal Hybrid Electricity Power Generating Systems

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Abstract: Botswana currently depends on electricity generated from coal-based power plant or electricity supplied from the border in South Africa. The country has good reserves of coal and the solar radiation is sufficiently high to make solar thermal attractive for generating electricity. The paper presents two conceptual coal-fired power station designs in which a solar sub-system augments heat to the feed heaters or to the boiler. The thermal and economic analyses showed enhanced system performance which indicates that solar power could be embedded into existing fossil fuel plants or new power stations. Integrating solar energy with existing or new fossil fuel based power plants could reduce the cost of stand-alone solar thermal power stations, reduce CO_2 emissions and produce experience necessary to operate a full scale solar thermal electricity generation facility.

Key words: Hybrid systems, solar, coal, economics, performance.

Nomenclature

A	Annuitized construction costs, $
CC	Total construction costs, $
dr	Discount rate
h	Specific enthalpy, kJ/kg
$\dot{m}_T$	Total system mass flow rate, kg/hr
Q	Heat input, kJ/kg
Q_s	Total solar input, kJ/hr
Q_{mc}	Maximum heat load for open feedwater heater, kJ/hr
Q_{sc}	Solar input to closed feedwater heater, kJ/hr
W	Pump of turbine work, kJ/kg
y_c	Fraction of total mass flow extracted for closed feedwater heater, dimensionless
η	Plant thermal efficiency
y_o	Fraction of total mass flow extracted for open feedwater heater, dimensionless

1. Introduction

Electricity requirements in Botswana are supplied through local generation at Morupule coal-based power station and imports from the Southern Africa Power Pool, mainly from Eskom of the Republic of South Africa (RSA). Botswana has abundant reserves of coal estimated at 212 billion tones in various fields though only one field is currently operational. With these huge coal resources it is likely that Botswana would depend on coal fired power stations for future electricity needs. Indeed several such power stations are at various stages of development to make the country self sufficient in electricity and possibly become a power exporter to neighbouring states. As CO_2 generated per capita will grow steadily, environmental issues would increasingly be of concern.

The country is a signatory to the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol to control greenhouse gas emissions. Some of the options under consideration to limit CO_2 emission from power stations include use of advanced power systems such as integrated gasification combined cycle (IGCC) systems and carbon sequestration technologies to recapture and store carbon dioxide (i.e. carbon capture and storage). To generate

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electricity on a long term basis there are aggressive plans to introduce renewable technologies especially solar thermal and biomass systems. Botswana has one of the highest solar radiation regimes in the world because the country receives over 3200 hours of sunshine per annum and the average daily insolation on a horizontal surface is approximately 21 MJ/m^2 [1]. From an economic, strategic and environmental point of view it is appropriate to promote the use of solar energy in Botswana. However, solar thermal electricity involves huge capital costs.

Current economic assessments place the cost of generating electricity using solar thermal power, including storage, at 0.16 $/kWh compared to hard coal at 0.05 $/kWh [2]. This has both discouraged investment in solar thermal power and negatively impacted innovation that results from operating experience with new facilities. Solar-coal hybrid thermal power plants have been proposed more recently as an economically viable alternative to stand-alone solar thermal power plants [3].

The advantage of the hybrid facility is that, in many locations, transmission capacity already exists whereas for a stand-alone solar facility transmission capability may not be available in locations where the solar radiation is sufficient to warrant investment in solar thermal generating plants. In addition, the solar-coal hybrid does not require storage which is estimated to be approximately 15% of the total cost of construction for a solar thermal facility utilizing parabolic trough technology [2]. Furthermore, the hybrid technology appears to offer retrofit potential for existing coal fired power plants located where annual solar radiation is sufficiently high. Finally, it may be possible to generate additional power without adding turbine capacity. Therefore, it is plausible to use hybrids of solar-coal as a transition stage to fully renewable energy production [3-5].

The current paper examined a "generic" coal fired facility located where the solar insolation is approximated by that at Morupule, the location of Bostwana's single coal-fired power plant. Two possible hybrid configurations are considered. In the first option the solar input is utilized to gradually replace feedwater heating. For this plant configuration (Fig. 1) the coal consumption is constant but the turbine output increases as solar energy replaces steam bled from the turbines in order to provide feedwater heat. The second configuration (Fig. 2) considered is one for which the solar input replaces a portion of the boiler heat reducing the quantity of coal as the solar input increases.

It was assumed that the first configuration would be easier to implement at an existing facility because the boiler does not require any modification. The only necessary change to the existing facility is the addition of heat exchangers to the feedwater heaters. However, it is likely to be more difficult to control because of the complexity of the feedwater heating scenario. The second configuration appears to be more straightforward in terms of control and, perhaps, more economical to implement during new construction. In both cases the amount of CO_2 produced per unit of electricity generated is reduced in comparison to the coal-fired power plant.

2. System Analysis

The generic Rankine cycle that is selected for analysis is a standard superheat cycle having re-heat and two feedwater heaters—one open and one closed [6]. The temperatures and pressures at various points in the cycle are shown in Table 1. This cycle has a thermal efficiency (reversible) of 43.1% [6] and a "parasitic" energy cost for feedwater heating amounting to about 18%. Just less than 25% of the total mass flow of steam is extracted for feedwater heating before the lowest pressure stages of the turbine. If all of the feedwater heating is supplied by solar energy the plant efficiency (reversible) could be increased to 51%, based on the same coal input, resulting in a significant increase in power output (assuming that the turbines can accommodate the additional steam flow rate).

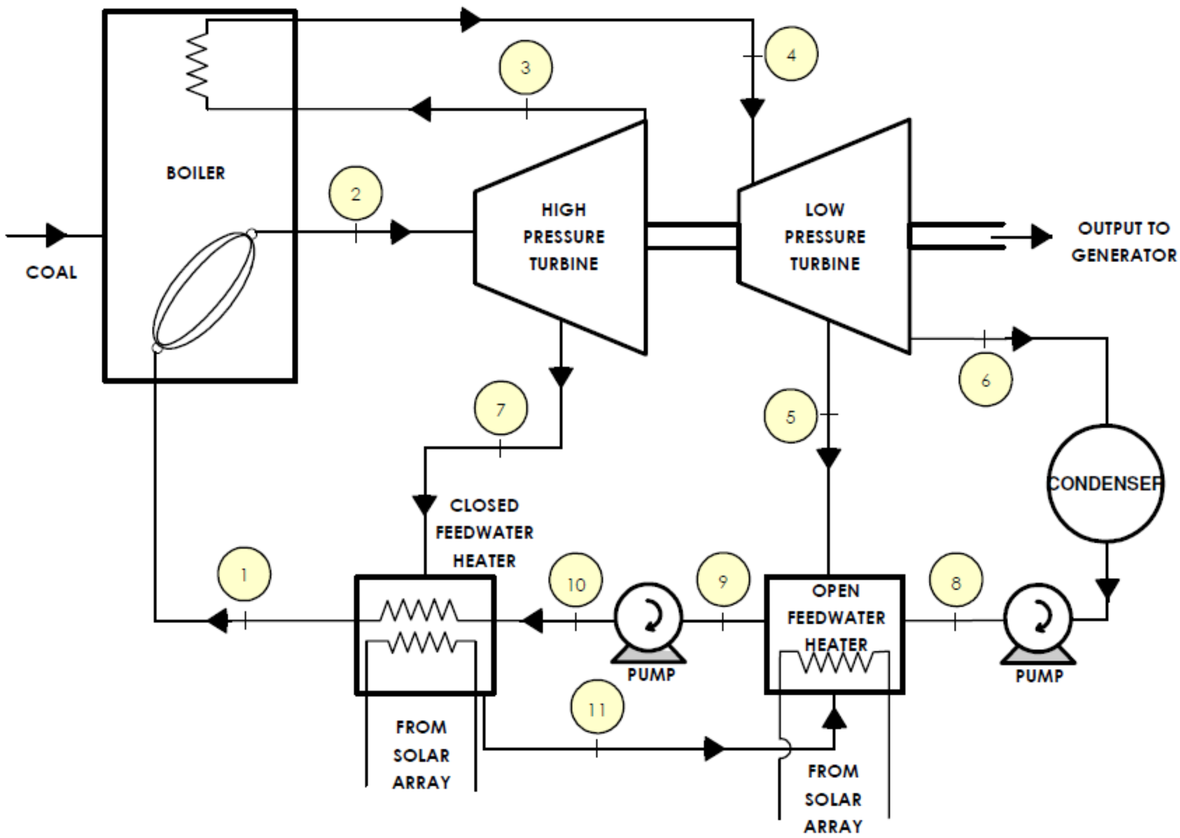

Fig. 1 Option 1—solar thermal feedwater heating.

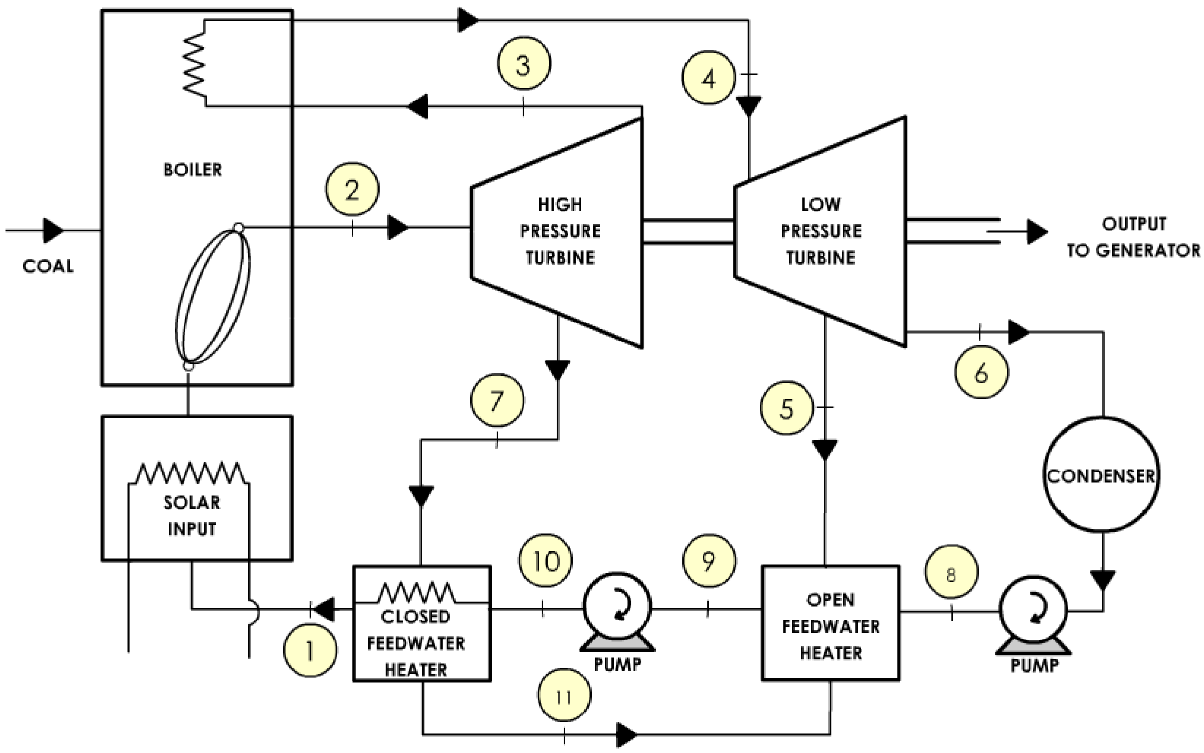

Fig. 2 Option 2—solar thermal input at boiler.

Table 1 Characteristics of basic Rankine cycle.

Operating characteristics	Value
Boiler inlet	205 °C, 8 MPa
Boiler (superheater) outlet	480 °C, 8 MPa
Closed feedwater heater inlet	2 MPa
High pressure turbine outlet	7 MPa
Low pressure turbine inlet	440 °C, 7 MPa
Open feedwater heater inlet	0.3 MPa
Low pressure turbine outlet	0.008 MPa
Condenser outlet	Saturated, 0.008 MPa
Open feedwater heater outlet	Saturated, 0.3 MPa
Power output (electric)-option 1	90-100 MW
Power output (electric)-option 2	100 MW
Steam rate	280,000 kg/hr
Boiler efficiency	90%
Generator efficiency	90%

For most of Botswana the average annual direct normal irradiance (DNI) ranges from 6.5-7.5 kWh/m^2. For the Morupule area the DNI is approximately 6.9 kWh/m^2 but a value of 6.75 kWh/m^2 was used in the current analysis to err on the conservative side. An east-west tracking on a polar axis was considered for parabolic trough collectors. The hourly irradiance is illustrated in Fig. 3 [7]. Fig. 3 includes the assumption of 75% efficiency for the parabolic trough field [7].

The results presented for both options are based on hourly calculations for one day per year which is assumed to be representative of the annual performance. For option 1 the solar heat is added to the feedwater heaters. Therefore, when the hourly solar input is less than the total heat load for the open feedwater heater will be given by:

$$Q_{mc}/\dot{m}_T = h_9 - (1 - y_c)h_8 - y_c h_{11} \quad (1)$$

The fraction of steam extracted for the open feedwater heater is given by:

$$y_o = \frac{h_9 - h_8 + y_c(h_8 - h_{11}) - Q_s/\dot{m}_T}{h_5 - h_8} \quad (2)$$

When the hourly solar input is greater than the total heat load for the open feedwater heater then a portion of the solar heat goes to the closed feedwater heater. For this case the enthalpy balances for the two feedwater heaters must be solved simultaneously to determine the fraction of steam extracted for the closed feedwater heater. The two enthalpy balances can be written (for $y_o = 0$)

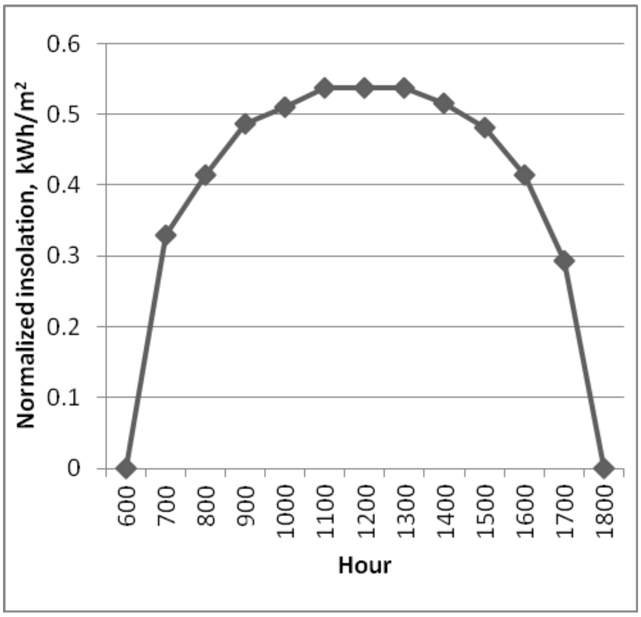

Fig. 3 Hourly direct normal irradiance.

$$(1 - y_c)h_8 + y_c h_{11} + Q_{mc}/\dot{m}_T = h_9 \quad (3)$$

$$y_c h_7 + h_{10} + Q_{sc}/\dot{m}_T = y_c h_{11} + h_1 \quad (4)$$

noting that $Q_{sc} = Q_s - Q_{mc}$

The work output by the turbines and work input to the pumps per total system mass flow rate are given by:

$$w_{t1} = (h_2 - h_7) + (1 - y_c)(h_7 - h_3) \quad (5)$$

$$w_{t2} = (1 - y_c)(h_4 - h_5) + (1 - y_c - y_o)(h_5 - h_6) \quad (6)$$

$$w_{p1} = (1 - y_c - y_o)(h_8 - h_{co}) \quad (7)$$

$$w_{p2} = h_{10} - h_9 \quad (8)$$

The total heat input is:

$$q_i = (h_2 - h_1) + (1 - y_c)(h_4 - h_3) \quad (9)$$

The turbine total output, pump inputs, and heat input were obtained for a 24 hour period and then the plant thermal efficiency was calculated, by dividing the net work by the heat input, i.e.

$$\eta = \left(w_{t1} + w_{t2} - w_{p1} - w_{p2}\right)/q_i \quad (10)$$

For option 2 the solar field was assumed to provide heat up to 350 °C. This allows for a much larger solar contribution to the 100 MW (thermal) plant than that for feedwater heating. The analysis is straightforward—as the hourly thermal input from the solar field increases the amount of thermal input from coal is decreased to maintain a constant plant output. The lower heating value for the coal is taken to be 20 MJ/kg.

For this scenario the turbine and pump work terms remain constant but the heat input from combustion process varies as the solar field contributes to the thermal input from the boiler. For this case,

$$q_i = q_{max} - q_{solar} \quad (11)$$

where, again, the solar input must be summed over the period when solar radiation is available and subtracted from the total daily heat load, q_{max} to obtain the thermal efficiency using Eq. (10).

3. Performance Analysis

In order to determine the economic performance, a variable size of collector field was employed for both configurations. Variable collector field costs were also investigated. The base cost is $\$500/m^2$ which is slightly more than that in the analysis by Kaltschmitt, et al. [2]. The annual operating and maintenance cost is assumed to be $\$10/m^2$ in current dollars and the cost of coal is assumed to be 0.030$/kg. For option 1 the base cost of construction for the solar facility is annuitized over the assumed plant life using:

$$A = CC\frac{dr(1+dr)^n}{(1+dr)^n - 1} \quad (12)$$

The annuitized construction costs along with the annual operating and maintenance costs are then used to compute the current cost per kilowatt-hour for the additional electricity generated. The plant life (n) is assumed to be 25 years. This leads to a determination of the optimum size for the solar contribution to the existing facility. In addition, it is important to establish the sensitivity of the solar field cost and performance assumptions. For this case the coal consumption remains constant and the coal-fired plant is assumed to be operational in situ.

The costs for construction and operation and maintenance for both the coal and solar facilities are included in the analysis for the second option. These costs for the solar part of the facility are assumed to be the same as those utilized in option 1. For the coal plant the construction costs are assumed to be 1.36×10^6 \$/MW and the annual operating and maintenance costs are assumed to be 50,000 \$/MW [2]. The coal plant capacity factor is assumed to be 0.8 leading to 7008 operating hours per year. The various costs and operating parameters employed in the economic analysis are summarized in Table 2.

4. Results and Discussion

The system thermal efficiency for option 1 without solar input is 43.1%. With solar input, as shown in Fig. 4, the efficiency increases to slightly above 46% as the size of the collector field is increased. The efficiency reaches a limit when the solar field provides all of the feedwater heating for the period when solar radiation is available. The results shown in Fig. 4 do not include the pumping costs for the working fluid in the solar field or other parasitic loads like the power used for tracking.

For option 1 the cost of the excess electricity generated in dollars per kilowatt hour is shown in Fig. 5 as a function of the size of the solar field in square meters. As illustrated in the figure there is an optimum solar field size of approximately 90,000 m^2 that results in the lowest cost for the electric power, just less than 0.108 \$/kWh for the $\$500/m^2$ field cost. For this case the solar field provides 5.8 MW in addition to the 90 MW (electric) delivered by combustion of coal. For a 6% discount rate this leads to an overall cost of electricity of just over 0.040 \$/kWh assuming the base cost of coal generated power to be 0.036 \$/kWh as computed for option 2. It was noted that, as a result of non-availability of solar input, particularly in the early morning and late afternoon hours, the results contain discontinuities. Fig. 5 shows that the cost of electricity per unit kilowatt hour increases as the assumed cost of the solar field increases. Therefore, augmentation of electricity production from fossil fuel plants with solar system will be attractive where insolation is very high. The effect of discount rate on the cost of electricity for this option is illustrated in Fig. 6.

Table 2 Parameters used in economic analysis.

Name of variable	Value
Cost of solar field, \$/m^2	300-700
Annual O &M for solar field, \$/m^2	10
Cost of coal, \$/kg	0.030
Plant life, yrs.	25
Construction costs for coal plant, \$/MW	1.36×10^6
Annual O &M for coal plant, \$/MW	50,000
Plant capacity factor	0.8 (7008 hr/yr)
Discount rate (dr), %	6-10

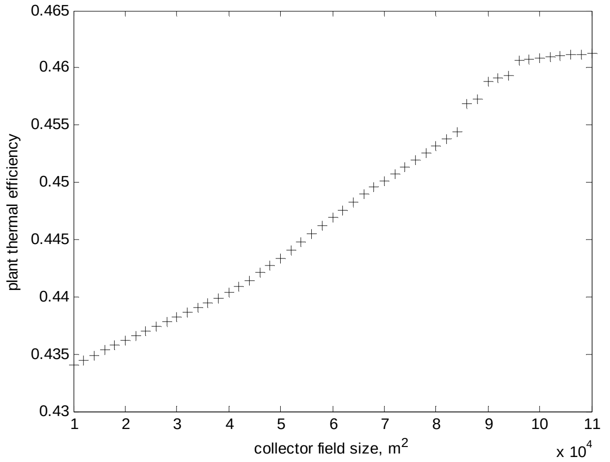

Fig. 4 Plant thermal efficiency versus collector field size for option 1.

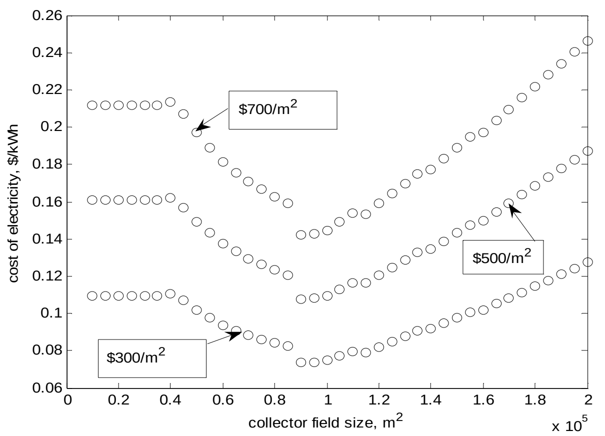

Fig. 5 Cost of excess electricity generated versus the size of the solar field for option 1.

For small solar fields, less than 40,000 m^2, the solar contribution affects only the open feedwater heater. As the fraction of steam extracted to supply heat to the feedwater heater decreases the output from the low pressure turbine increases in proportion to the enthalpy difference between the extraction point and the turbine outlet. The result is a constant estimated

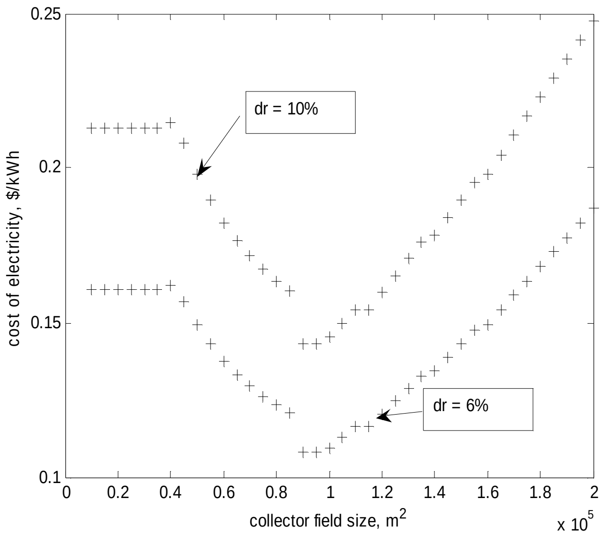

Fig. 6 Cost of excess electricity generated for option 1 for 2 discount rates (dr).

cost for the extra power produced of just over 0.16 \$/kWh. For solar fields above 40,000 m^2 the solar input begins to contribute to the closed feedwater heater increasing the output from both the high and low pressure turbines. This causes the cost of extra power produced via solar to decrease significantly to just under 0.11 \$/kWh as mentioned above.

With 90,000 m^2 of collector field all of the feedwater heat is supplied by solar energy for 5 hours of the day. Fig. 7 illustrates the quantity of excess electricity generated as a function of the size of the collector field. The optimum design (minimum cost of excess power generation) occurs slightly before the solar energy input reaches the point of supplying the entire feedwater load for the sunshine period (11-hour day) analyzed. For example, if the collector field is increased to greater than 160,000 m^2 all of the feedwater load is covered (11 hours per day) resulting in 7.5 MW of extra power at a cost of 0.1439 \$/kWh (6 MW when multiplied by the plant capacity factor of 0.8). The average cost for power produced by the hybrid facility is then 0.044 \$/kWh.

For option 2 the plant thermal efficiency increases as indicated in Fig. 8 beginning at 43.1% for no solar contribution and peaking at 63.4% when the solar field provides the maximum possible (350 ^{o}C at 8 MPa) for the 11 hours in which solar radiation is available. As

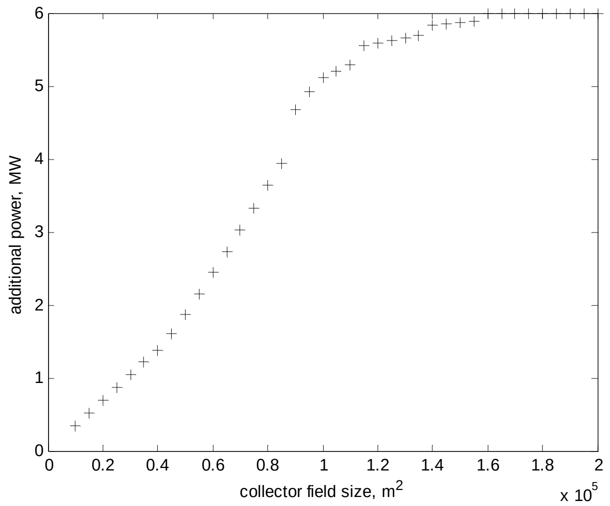

Fig. 7 Excess electricity generated by option 1 as a function of solar field size.

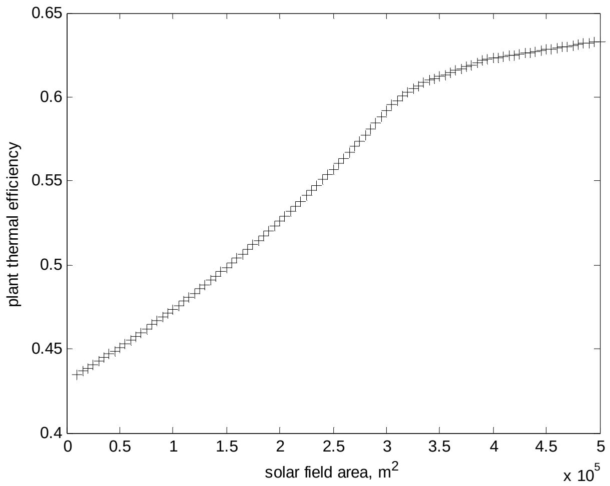

Fig. 8 Plant thermal efficiency as a function of solar field size for option 2.

for the option 1 analysis the parasitic losses associated with the solar field, pumping and tracking power, are not considered when calculating the plant thermal efficiency.

As indicated above, for option 2 the base cost of electricity generated from coal at a 6% discount rate is 0.036 \$/kWh. As illustrated in Fig. 9 the average cost of electricity increases as the size of the solar contribution is increased. However, the cost is much less than it would be for 100% solar, particularly if storage is included. For example, for a 200,000 m^2 the estimated electricity cost is 0.050 \$/kWh providing 19 MW (electricity) of the total 100 MW. With 400,000 m^2 of solar resource the solar contribution is 30.9 MW at

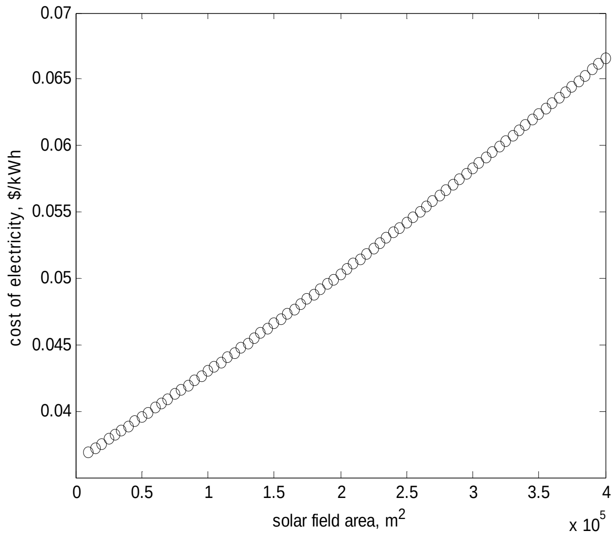

Fig. 9 Average cost of electricity for option 2 as a function of solar field size.

a cost of 0.066 \$/kWh. The solar heat was assumed to be available at a maximum temperature of 350 ^oC, thus, if the size of the collector field is increased significantly above 400,000 m^2 the average cost of the electricity produced increases rapidly because all of the energy collected is not utilized.

5. Conclusions

The results illustrate that solar-coal hybrid plants can produce electricity at costs only slightly greater than those for coal-fired power plants. Utilizing solar thermal for feedwater heating demonstrated that by adding solar energy system to an existing facility potentially increased the power output by 5%-8% while only very modestly increasing the power cost. One of the advantages of this approach is that it allows the construction of a small solar thermal unit without storage or transmission that will produce power at a moderate increase over coal and increase the total output from an existing plant. It also allows for the establishment of local construction and operating and maintenance costs without the construction of a larger and potentially more risky stand alone solar thermal facility.

Option 2 which utilizes solar thermal to replace coal at the boiler may be more applicable to new power plant installation. For this case providing 20% to 25%

of the total plant capacity with solar can be accomplished with a modest increase in the cost of the electricity generated. This may be attractive in regions where the peak load is a result of summer air conditioning demand and corresponds with the peak in solar radiation.

In conclusion, integrating solar thermal power with existing or new fossil fuel-based power plants is a useful strategy to reduce the cost of stand-alone solar thermal power stations, reduce CO_2 emissions and gain low risk experience necessary to operate a full scale solar thermal electricity generation facility.

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