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SOLAR AUGMENTATION AT SUPERCRITICAL COAL-FIRED POWER STATIONS

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ABSTRACT

Conventional concentrating solar power (CSP) plants typically have a very high levelised cost of electricity (LCOE) compared with coal-fired power stations. To generate 1 kWh of electrical energy from a conventional linear Fresnel CSP plant without a storage application, costs the utility approximately R3,08 [1], whereas it costs R0,711 to generate the same amount of energy by means of a highly efficient supercritical coal-fired power station, taking carbon tax into consideration.

This high LCOE associated with linear Fresnel CSP technology is primarily due to the massive capital investment required per kW installed to construct such a plant along with the relatively low-capacity factors, because of the uncontrollable solar irradiation. It is expected that the LCOE of a hybrid plant in which a concentrating solar thermal (CST) station is integrated with a large-scale supercritical coal-fired power station, will be higher than that of a conventional supercritical coal-fired power station, but much less than that of a conventional CSP plant. The main aim of this study is to calculate and then compare the LCOE of a conventional supercritical coal-fired power station with that of such a station integrated with a linear Fresnel CST field.

When the thermal energy generated in the receiver of a CST plant is converted into electrical energy by using the highly efficient regenerative Rankine cycle of a large-scale coal-fired power station, the total capital cost of the solar side of the integrated system will be reduced significantly, compared with the two stations operating independently of one another for common steam turbines, electrical generators and transformers, and transmission lines will be utilised for the integrated plants.

The results obtained from the thermodynamic models indicate that if an additional heat exchanger integration option for a 90 MW (peak thermal) fuel-saver solar-augmentation scenario, where an annual average direct normal irradiation limit of 2 141 kWh/m^2 is considered, one can expect to produce approximately 4,6 GWh more electricity to the national grid annually than with a normal coal-fired station. This increase in net electricity output is mainly due to the compounded lowered auxiliary power consumption during high solar-irradiation conditions. It is also found that the total annual thermal energy input required from burning pulverised coal is reduced by 110,5 GWh, when approximately 176,5 GWh of solar energy is injected into the coal-fired power station's regenerative Rankine cycle for the duration of a year. Of the total thermal energy supplied by the solar field, approximately 54,6 GWh is eventually converted into electrical energy. Approximately 22 kT less coal will be required, which will result in 38,7 kT less CO_2 emissions and about 7,6 kT less ash production.

This electricity generated from the thermal energy supplied by the solar field will produce approximately R8,188m in additional revenue annually from the trade of renewable energy certificates, while the reduced coal consumption will result in an annual fuel saving of about R6,189m. By emitting less CO_2 into the atmosphere, the annual carbon tax bill will be reduced by R1,856m, and by supplying additional energy to the national grid, an additional income of approximately R3,037m will be due to the power station. The annual operating and maintenance cost increase resulting from the additional 171 000 m^2 solar field, will be in the region of R9,71m.

The cost of generating 1 kWh with the solar-augmented coal-fired power plant will only be 0,34 cents more expensive at R0,714/kWh than it would be to generate the same energy with a normal supercritical coal-fired power station.

INTRODUCTION

For the last decade, Eskom's electricity network has been under immense pressure, which has eventually resulted in load shedding and a number of expensive load managing/reduction projects. This electricity shortfall is attributable mainly to an inadequate increase in generation capacity and the fast-growing electricity demand from its consumers. This also has a major impact on the maintenance schedules of the existing power stations, which may snowball into an even greater electricity supply shortfall.

As the literature clearly indicates, renewable energy sources have a relatively poor capacity factor compared with conventional coal-, gas- and nuclear-based power generation methods. But, electricity generation via renewable energy sources has two very important advantages that contribute significantly to the financial feasibility of such projects:

Firstly, the fuel or energy resource is free of charge for renewable energy methods (with the exception of some hydro schemes). This means that a power station utilising such resources will not have a fuel cost incorporated in its levelised cost of electricity calculation.

Secondly, there are no harmful emissions to the environment, which means that no carbon tax and environmental penalty costs are considered. At this stage (January 2015), no green credits or tradable renewable energy certificates (TRECs) have a major impact on the South African renewable energy industry. Even though TRECs are not yet in full effect in South Africa, the potential incorporation thereof is considered in this study.

Renewable energy does, however, also have a huge downside: it has a high levelised cost of electricity generation. This is mainly because of low capacity factors and high capital and maintenance costs associated with these plants.

Fuel-based (coal, gas, nuclear) electricity generation methods have high capacity factors, but also have a high fuel cost and discharge harmful emissions (SO_x, NO_x, CO_2, nuclear waste) to the environment. On the other hand, renewable energy power generation methods have low capacity factors, zero fuel costs and zero harmful emissions.

The augmentation concept, specifically solar augmentation, marries the abovementioned methods of power generation. In this hybrid concept, an existing coal-fired power station is integrated with a solar thermal plant, specifically CST. By doing so, the thermal heat produced by the CST field is fed into the Rankine cycle of the existing coal-fired power station. By doing so, one can either keep the gross electricity production rate constant while saving fuel, or one can boost/increase the electricity output capacity of the coal-fired station. Except for the fact that the capital cost of just the solar field will be very low compared with a conventional CSP plant (because the coal station's turbines, generators, transformers, switchgear and transmission lines are utilised), both these operating modes have their own advantages as well:

In boosting mode, the fuel consumption and harmful emissions levels will not necessarily decrease, but more electricity can be generated and will be available to the constrained grid.

In fuel-save mode, no additional electricity will be generated, but less coal will be burned, less harmful gases will be emitted, and less ash will have to be handled. This mode can also reduce the operating cost of the power station (fuel-cost decrease, carbon-tax decrease, income from TRECs, own electricity consumption decrease, etc).

NOMENCLATURE

Abbreviations

CSP	[-]	Concentrating solar power
CST	[-]	Concentrating solar thermal
LCOE	R/kWh	Levelised cost of electricity
CO_2	[-]	Carbon Dioxide
SO_x	[-]	Sulphur Oxides
NO_x	[-]	Nitrogen Oxides
TREC	[-]	Tradable renewable energy certificate
SAPG	[-]	Solar assisted power generation
EES	[-]	Engineering equation solver
DNI	[W/m^2]	Direct normal irradiation
HPT	[-]	High pressure turbine
IPT	[-]	Intermediate pressure turbine
LPT	[-]	Low pressure turbine
HPH	[-]	High pressure heater
LPH	[-]	Low pressure heater
DST	[-]	Deaerator storage tank
BFP	[-]	Boiler feed pump
MCR	[%]	Maximum continuous rating
SAM	[-]	System Advisor Model
NREL	[-]	National Renewable Energy Laboratory

Subscripts

t	Thermal
e	Electrical
m	Mechanical

The solar augmentation or solar-assisted power generation (SAPG) concept integrates the advantages of a concentrating solar thermal plant with the advantages of a coal-fired power station. Basically explained, the thermal energy generated in a solar field's collectors is injected at strategic integration points of a coal-fired power station's regenerative Rankine cycle and is not directly used for power generation.

According to [2], the annual electricity produced by the solar thermal energy injected into a coal-fired power station is more than 25% greater than can be expected from a stand-alone CSP plant. Also, if it is assumed that the cost of an SAPG plant is approximately 72% of the cost of a stand-alone CSP plant, an SAPG is 1,8 times more cost effective than a stand-alone CSP plant [2].

Depending on the limitation parameters of the coal-fired station, a solar augmentation scenario may be operated in two main operation modes [3]:

- Boosting mode
- Fuel-saver mode

According to [4], the basis of the SAPG concept is to use solar thermal energy to replace the bled-off steam used for feedwater preheating. By doing so, less or no steam will have to be tapped off from the turbines, because the energy required for feedwater preheating comes from the solar field.

[5] found in 2010, during a thermodynamic analysis of a sub- and supercritical coal-fired power station, that approximately 5-6% fuel can be saved when solar energy is used for feedwater preheating. It was also found that the annual reduction in coal consumption is about 49 600 tonnes, the annual reduction in ash production is approximately 24 300 tonnes, while the plant's CO_2 emissions can decrease by up to 62 000 tonnes for a 500 MWe power plant (subcritical) [5].

METHODOLOGY

A thermodynamic model of an 800 MW supercritical coal-fired power station, in which all major input and output variables are calculated, was developed with Engineering Equation Solver (EES), a thermodynamic software package. A thermodynamic model of the same power station was then developed with ThermoFLEX, which is also a thermodynamic software package, to verify the EES model's input and output parameters. These parameters are then used to calculate the LCOE of this stand-alone coal-fired power station in Microsoft Excel. Henceforth, this stand-alone power station will also be referred to as the base-case scenario.

A thermodynamic model of a scenario, where thermal energy generated in a solar field is injected into the regenerative Rankine cycle of the base-case scenario, was then developed in EES. Actual data collected from Eskom's linear Fresnel pilot and demonstration plant at Rosherville was used to calculate an accurate "solar to thermal" efficiency for such a CST technology. This efficiency was then used as an input parameter to calculate the amount of thermal energy available to the coal-fired power station, from the solar field in the solar augmentation models.

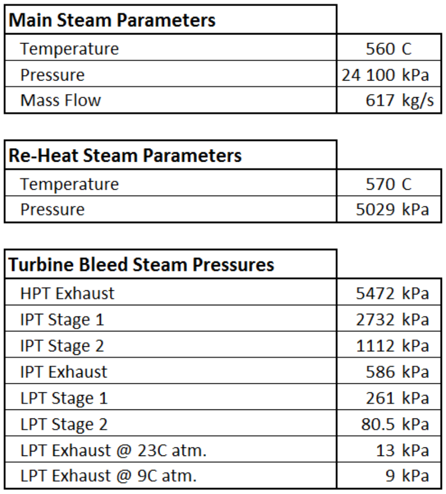
Parametric tables, in which the direct normal irradiation (DNI) was varied according to typical irradiation days, were then developed in EES, in which the major input and output parameters were calculated on a five-minute basis. This data was then used to calculate summarised annual parameters, typical to the Mpumalanga region, that were then used to calculate the LCOE of the solar augmented scenario.

BASE CASE SCENARIO

The steam entering the high pressure turbine (HPT) of the base case scenario has a temperature of 560 °C at 24,1 MPa and a flow rate of 617 kg/s, while the reheated steam, entering the intermediate pressure turbine (IPT), has a temperature and pressure of 570 °C and 5 029 kPa.

The steam at the HPT exhaust has a pressure of 5 472 kPa. The steam at the IPT's first extraction point has a pressure of 2 732 kPa, the steam at the second extraction point has a pressure of 1 112 kPa, and the steam at the IPT exhaust has a pressure of 586 kPa. It is assumed that the low pressure turbine (LPT) exhaust steam has a pressure of 13 kPa when the atmospheric temperature is 23 °C and 9 kPa when it is 18 °C, while the steam at the first LPT extraction point has a pressure of 261 kPa and 80,5 kPa at the second. These parameters are similar to those of Kusile, Eskom's new supercritical power station. These main design parameters at full load conditions are illustrated in Table 1.

Table 1: Main design parameters at full load



Main Steam Parameters	
Temperature	560 C
Pressure	24 100 kPa
Mass Flow	617 kg/s

Re-Heat Steam Parameters	
Temperature	570 C
Pressure	5029 kPa

Turbine Bleed Steam Pressures	
HPT Exhaust	5472 kPa
IPT Stage 1	2732 kPa
IPT Stage 2	1112 kPa
IPT Exhaust	586 kPa
LPT Stage 1	261 kPa
LPT Stage 2	80.5 kPa
LPT Exhaust @ 23C atm.	13 kPa
LPT Exhaust @ 9C atm.	9 kPa

The regenerative Rankine cycle considered in this study is illustrated in Figure 1.

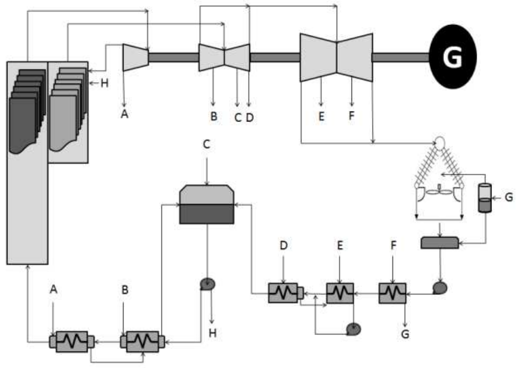


Figure 1: Base case regenerative Rankine cycle

Where:

A = Bled-off steam from HPT exhaust to high pressure heater (HPH) 6 A and B
B = Bled-off steam from IPT (1st stage) to HPH5 A and B
C = Bled-off steam from IPT (2nd stage) to deaerator
D = Bled-off steam from IPT exhaust to low pressure heater (LPH) 3
E = Bled-off steam from LPT (1st stage) to LPH2
F = Bled-off steam from LPT (2nd stage) to LPH1
G = Condensate from LPH1 to condenser flash box
H = Spray water from boiler feed pump (BFP) (interstage) to attemperator

The temperature vs. entropy (T-s) diagram for the modelled base case supercritical cycle is illustrated in Figure 2.

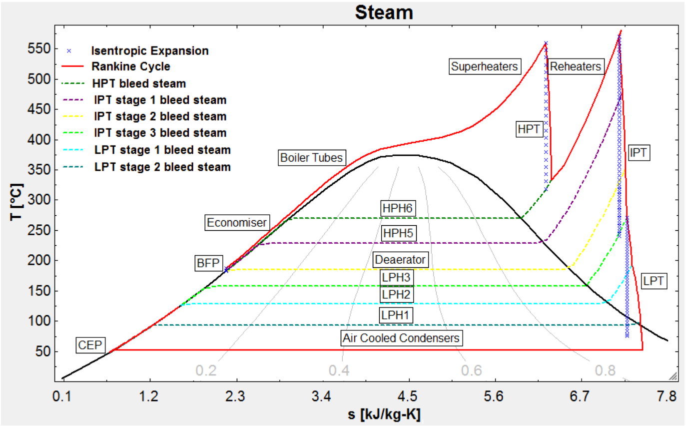


Figure 2: T-s diagram of base case Rankine cycle

Base Case Scenario Summary

From the EES models it is calculated that an 800 MWe supercritical coal-fired power station at its 100% maximum continuous rating (MCR), can generate approximately 795 033 kWe from the available 803 875 kWm shaft power. The station will be able to push 729 574 kWe into the national grid after the 65 458 kWe for the auxiliary systems is subtracted. The furnace requires a heat input of 1 896 426 kWt from coal, of which approximately 1 706 783 kWt is absorbed into the Rankine cycle for power generation.

The net cycle efficiency of this supercritical unit is 42,7%, while the overall efficiency (coal to electricity out) is around 38,5%. The major performance parameters of this base-case, coal-fired power station can be seen in Table 2.

Table 2: Base-case performance parameters

Base Case Performance Parameters at 100% MCR	
Total Shaft Power	803875 kWm
Gross Electricity Output	795033 kWe
Total Auxiliary Electricity Consumption	65458 kWe
Net Electricity Output	729574 kWe
Total Heat Added to Furnace	1896426 kWt
Heat Absorbed to Rankine Cycle	1706783 kWt
Net Cycle Efficiency	42.7 %
Gross Cycle Efficiency	46.6 %
Net Overall Efficiency	38.5 %

If a full year is considered, the unit will supply approximately 5 812,7 GWh of electrical energy to the national grid per year from a 13 652,4 GWh thermal heat input by burning pulverised coal.

Approximately 2 716,9 kT of coal will be burned throughout the year, which will result in approximately 937,3 kT of ash, 4 800,4 kT of CO_2 and 59,2 kT of SO_2 per year. The major input and output parameters of the base-case study can be seen in Table 3.

Table 3: Major base case input and output parameters

Base Case Input and Output Parameters	
Net Electricity Out	5812.7 GWh/Year
Total Heat Input (from coal)	13652.4 GWh/Year
Total Coal Consumption	2716.9 kT/Year
Total CO2 Emissions	4800.4 kT/Year
Total Ash	937.3 kT/Year
Total Solar Energy Input	0.0 GWht/year
Total Electricity from Solar Power	0.0 GWhe/year

All cost multiplying factors for the base case power station were taken from the Electric Power Research Institute (EPRI) report: "Power Generation Technology Data for Integrated Resource Plan of South Africa" [6].

The overnight cost of such a coal-fired power station will be in the region of R14 228m, while the fuel will cost approximately R764,5 m per year, the total O&M cost will be about R622m per year and carbon tax will cost the station approximately R230,4 m per year.

Table 4: Base-case major expenses

Major Expenses	
Capital Cost	R 14 228 000 000 once off
Fuel Cost	R 764 539 908 per year
Carbon Tax Cost	R 230 420 938 per year
O&M Cost	R 622 084 163 per year

When all the expenses are discounted back to year zero and divided by the total discounted electricity generated over the lifetime of the plant, it is found that an 800 MWe supercritical coal-fired power station has an LCOE of approximately R0,711 per kWh, when a carbon tax rate of 48 cents per ton of CO_2 is assumed.

It is assumed that the specific coal-fired power station will be at 100% MCR from 6:00 to 23:00. During the late nights and early mornings of every day the station will operate at 60% MCR. The gross generator power output for a single day vs time can be seen in in Figure 3 below.

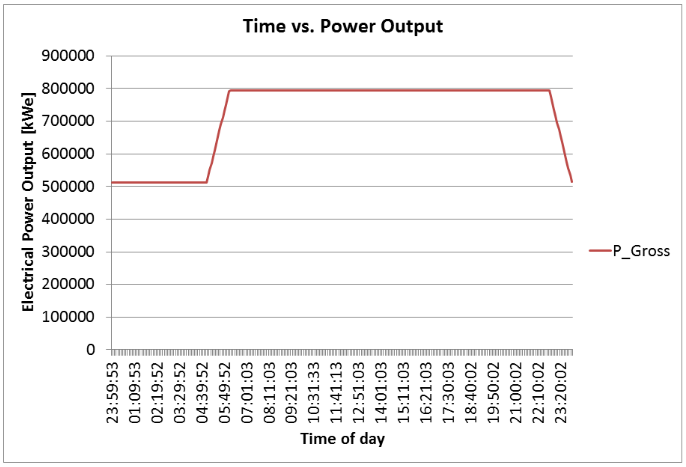


Figure 3: Generator gross capacity vs time of day

SOLAR AUGMENTATION SCENARIO

Only one solar augmentation scenario is considered in this study. In this scenario an additional heat exchanger is installed in the HPH bypass line. The quantity of feedwater pumped through the additional heat exchanger will be determined by the available solar radiation at the time. It is assumed that the CST technology can produce temperatures of up to 300 °C at 6 000 kPa (60 bar).

The main limiting parameter for this study is the minimum reheater attemperation spray-water flow rate of 3 kg/s. If the solar to thermal efficiency calculated at the Rosherville pilot and demonstration plant is assumed to be (48%), it is calculated that under peak solar irradiation conditions (1 100 W/m^2), the maximum thermal power that can be injected into the coal-fired power station, before the spray water drops below the minimum value, is 90 MWt. To generate this thermal power at peak solar conditions, a collector field with a 171 000 m^2 collector area is required.

Table 5: Solar field assumptions

Linear Fresnel CST	
Maximum Output Temperature [C]	300 C
Maximum System Pressure [kPa]	6000 kPa
Thermal Power Output @ 1100W/m^2 [kWt]	90288 kWt
Solar to Thermal Eff. [%]	48 %
Total Collector Area [m^2]	171000 m^2

Depending on the DNI at the time, a calculated amount of feedwater will be bypassed past the high- pressure heaters. This bypassed water will be heated by an additional closed heat exchanger powered by the working fluid from the solar field (Figure 4).

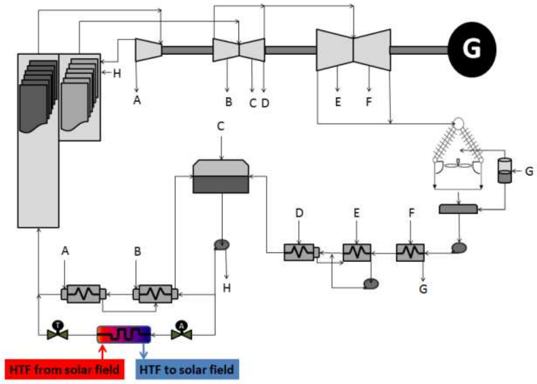


Figure 4: Illustration of additional heat-exchanger scenario

The amount of bypassed water will be controlled by the automated flow-control valve (Figure 5) so that the feedwater leaving the additional heat exchanger will be at the same temperature as the water leaving the final high-pressure heaters. The throttle valve is situated behind the additional heat exchanger and is responsible for throttling the pressure of the bypassed water down to approximately the same pressure as the feedwater leaving the final high-pressure heaters.

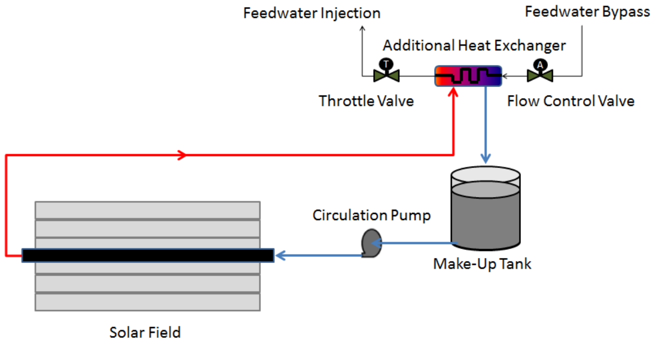


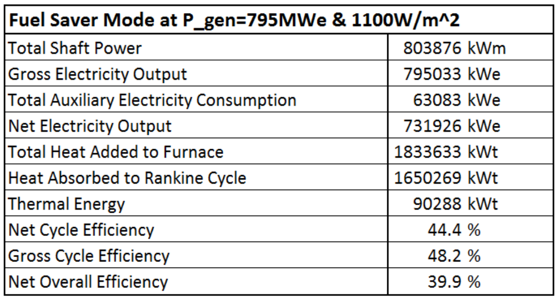
Figure 5: Basic illustration of the solar cycle

As the DNI increases from sunrise to midday, the control valve will bypass more water through the additional heat exchanger, as more thermal energy is generated by the solar field to be exchanged to the feedwater. In effect, less feedwater will flow through the conventional high- pressure heaters, which will decrease the bleed steam required to heat the feedwater to the required temperature. This will result in an increased mass flow through the IP and LP turbines, which will increase the shaft power output as well. The mass flow through the reheater will also increase and will affect the attemperation spray water quantity. The spray water flow rate will not be allowed to fall below 3 kg/s to ensure that there is adequate temperature control over the feedwater during the reheat cycle.

Solar Augmentation Scenario Summary

When a fuel-save scenario, where the generator output capacity has a maximum value of 795 033 kWe and the peak solar irradiation rating of 1 100 W/m^2, is considered, it is found that the boiler requires only 1 833 633 kWt from coal to reach full generating capacity. In effect, the generator is operating at full load but the boiler is only at 95% MCR. It is also found that the net electrical output to the national grid is slightly higher at 731 926 kWe because of the reduced auxiliary power consumption (63 083 kWe). The major performance parameters for the fuel- saver scenario are shown in Table 6.

Table 6: Fuel-saver mode parameters

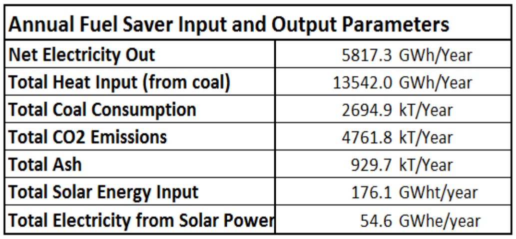


Fuel Saver Mode at P_gen=795MWe & 1100W/m^2	
Total Shaft Power	803876 kWm
Gross Electricity Output	795033 kWe
Total Auxiliary Electricity Consumption	63083 kWe
Net Electricity Output	731926 kWe
Total Heat Added to Furnace	1833633 kWt
Heat Absorbed to Rankine Cycle	1650269 kWt
Thermal Energy	90288 kWt
Net Cycle Efficiency	44.4 %
Gross Cycle Efficiency	48.2 %
Net Overall Efficiency	39.9 %

When a full year is considered, where an annual solar irradiation rating of 2 141 kW/m^2 is assumed with a linear Fresnel thermal capacity factor of 22,2%, the following annual input and output parameters for a fuel-saver scenario are calculated.

A total amount of 5 817,3 GWh of electrical energy can be fed into the national grid by burning only 2 694,9 kT of coal. The CO_2 emission rate is lowered to 4 761,8kT per year, while the amount of ash produced during a year is reduced to 929,7 kT. The annual fuel-saver scenario performance parameters can be seen in Table 7.

Table 7: Annual input and output parameters for a fuel-saver scenario



Annual Fuel Saver Input and Output Parameters	
Net Electricity Out	5817.3 GWh/Year
Total Heat Input (from coal)	13542.0 GWh/Year
Total Coal Consumption	2694.9 kT/Year
Total CO2 Emissions	4761.8 kT/Year
Total Ash	929.7 kT/Year
Total Solar Energy Input	176.1 GWht/year
Total Electricity from Solar Power	54.6 GWhe/year

All cost multiplying factors for the additional solar field was taken from the freeware package, “System Advisor Model” (SAM), developed by the National Renewable Energy Laboratory (NREL).

The overnight cost of such a hybrid power station, where renewable resources and fossil fuels are utilised, will be in the region of R14 898,354m, while the fuel cost will come down to approximately R758,35m per year, the total O&M cost will increase to about R631,796m per year and carbon tax will cost only R228,56m per year. Because 54,6 GWh of electrical energy is generated with a renewable resource, R8,188m is earned by selling TRECs.

Table 8: Solar augmentation major expenses

Major Expenses			
Capital Cost	R	14 898 354 200	once off
Fuel Cost	R	758 350 166	per year
Carbon Tax Cost	R	228 564 755	per year
O&M Cost	R	631 796 963	per year

When all the expenses are discounted back to year zero and divided by the total discounted electricity generated over the lifetime of the hybrid plant, it is found that an 800 MWe supercritical coal-fired power station, combined with a 90 MWt solar field, has an LCOE of approximately R0,715 per kWh.

CONCLUSION

The results from the thermodynamic models indicate that if an additional heat exchanger integration option for a fuel-saver solar augmentation scenario is considered, one can expect to produce approximately 4,6 GWh of net electricity in addition to what can be generated in the base-case scenario. This increase in net electricity output is mainly due to the compounded lowered auxiliary power consumption during high solar irradiation conditions.

It is also found that the total thermal energy input required from burning pulverised coal is reduced by 110,5 GWh, while approximately 176,5 GWh of solar energy is injected into the coal-fired power station's regenerative Rankine cycle throughout the year. Of this total thermal energy supplied by the solar field, approximately 54,6 GWh is eventually converted into electrical energy. Approximately 22 kT less coal will be required, which will result in 38,7 kT less CO_2 emissions and about 7,6 kT less ash production.

All major input and output parameters, as well as the LCOE for the base-case vs the solar augmentation case, are summarised in Table 9.

Table 9: Base-case vs solar augmentation results

	Units	Base Scenario	Augmentation Scenario	Offset
Net Electricity Out	GWh/Year	5812.7	5817.3	4.6
Total Heat Input (from coal)	GWh/Year	13652.4	13542.0	-110.5
Total Coal Consumption	kT/Year	2716.9	2694.9	-22.0
Total CO2 Emissions	kT/Year	4800.4	4761.8	-38.7
Total Ash	kT/Year	937.3	929.7	-7.6
Total Solar Energy Input	GWht/year	0	176.1	176.1
Total Electricity from Solar Power	GWhe/year	0	54.6	54.6
Levelised Cost of Electricity	R/kWh	0.7116	0.715	0.0034

If all input and output parameters are considered for a 35-year plant lifetime, it is found that the levelised cost of electricity for the solar augmentation scenario is approximately R0,715 per kWh.

This electricity generated from the thermal energy supplied by the solar field will annually produce approximately R8,188m additional revenue from the trade of renewable energy certificates, while the lowered coal consumption will result in an annual fuel saving of about R6,189m. By emitting less CO_2 into the atmosphere, the annual carbon tax bill is reduced by R1,856m and supplying additional energy to the national grid, an additional income of approximately R3,037m will be due to the power station. The annual operating and maintenance cost increase, due to the additional 171 000 m^2 solar field, will be in the region of R9,71m, while the overnight capital cost for the additional solar field and integration requirements will be about R670,354m.

Table 10: Annual operating cost deviation.

Annual Operating Cost Deviation	
Fuel Cost Saving	R 6 189 741.81
Carbon Tax Saving	R 1 856 182.68
TREC Income	R 8 188 697.12
Additional Electricity Sales	R 3 037 063.87
Increased O&M	R -9 712 800.00

The cost of generating 1 kWh with the solar augmented coal-fired power plant will only be 0,34 cents more expensive than it will be to generate the same energy with a normal supercritical coal-fired power station.

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