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ECONOMIC EVALUATION OF HYBRID SOLAR-COAL POWER PLANT

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1. Summary

Coal is a major economic commodity in Australia. The Australian coal industry is regarded as the most established and efficient in the world, producing some of the world's top-quality coal. This is attributed to world-class mines, supporting infrastructure and a highly skilled workforce employed in the industry. All these factors contribute to Australia being one of the world's largest producers of coal. At present, black and brown coals make up about 75% of Australia's electric generating capacity and the combined total is expected to remain dominant with a modest decrease to 68% in the next 20 years [ABARE, 2008]. Apart from the existing coal infrastructure, the continued reliance on coal is largely attributed to its low cost and abundant availability, as well as high reliability of coal power plants.

While coal seems to remain an important energy source in the immediate future, there is a growing number of factors that support renewable power generation, such as more stringent environmental regulations, technology improvements and increasingly available government clean energy grants and incentives (such as Renewable Energy Certificates – REC's). In the case of Australia, solar energy is specifically identified as a high-potential resource where a large fraction of the land mass experiences prolonged and high intensity solar exposure and high irradiation intensity, particularly in the northern mainland, towards the equator.

Even so, it is widely acknowledged that the practical installation of stand-alone solar power plants is hampered by high costs and diurnal power output. In the present analysis, a case study was carried out to evaluate the integration of a solar system with a coal-fired boiler as a single power plant environment with a combined generation capacity of 100 MWe, suitable to provide electricity with reduced greenhouse gas (GHG) intensity for mining operations. During periods of solar availability, coal derived steam is replaced by that from the solar plant, designed to produce 20 MWe at the steam turbine. Consequently, this replacement reduces coal usage and emissions, resulting in savings on fuel, operations, maintenance and taxes on carbon emissions.

For the purpose of economic evaluation, a base case of equivalent-capacity (100 MWe) power plant fuelled by coal only (no solar contribution) was also developed. It was shown that a carbon tax up to \$50/t-CO_2 reduces the cost gap between a solar/coal hybrid facility and the base case coal plant. However, for this particular case the economics of the hybrid system becomes more competitive with respect to the coal option when government-funded renewable grants, in the order of \$25-100 million, are incorporated into the economic model.

2. Introduction

More stringent environmental policies, commitment to the Kyoto Protocol (and no doubt its successor) and the general increase of community concerns mandates the need for power generators to increase efforts in minimizing GHG emissions. This directly affects coal-based power generators currently producing 75% of Australia’s power [ABARE, 2008].

The Australian Government’s Department of Climate Change reported that the GHGs produced as a result of electricity generation for direct consumption in the mining sector have increased 64.7% in 2007 (relative to 1990 base levels) – highest rate among all economic sectors: manufacturing; residential; services, construction and transport; and agriculture, forestry and fishing [Department of Climate Change, 2009].

Although it seems that in the near future power generators will still be dependent on coal, there is an urgent need to explore various strategies to make such processes more acceptable through reduced emission levels and align with government strategies. Ultimately, this brings forward the option of retrofitting parabolic trough solar collectors – a commercially-proven solar technology – into a coal-fired plant to produce cleaner electricity [Wibberley et al., 2006].

3. Objectives

In summary, the objectives of the current study are to:

a) Investigate the feasibility of integrating concentrating solar and coal-fired power to provide base load electricity;

b) Evaluate the reduction in carbon emission (in terms of t-CO_2/MWh) resulting from the integration of solar energy; and

c) Provide a comparison of economic indicators, such as Net Present Cost and electricity cost ($/MWh), between the cases of solar/coal hybrid and coal only.

4. Basic Plant Features

The solar field is comprised of parabolic troughs which concentrate solar irradiance onto central, tubular receivers. A hot transfer fluid (HTF, generally a diphenyl/biphenyl fluid blend) is circulated throughout the troughs, arranged in parallel. The inlet temperature of the HTF to the solar field is 290°C and exits at 395°C. This HTF is then circulated back to the powerhouse, whereby it superheats steam to 370°C at 29 bar. Two heat exchangers are employed, a superheater and steam generator, both operating in counter-current flow. The superheated steam is then integrated into the existing steam cycle through the STG, see Figure 1.

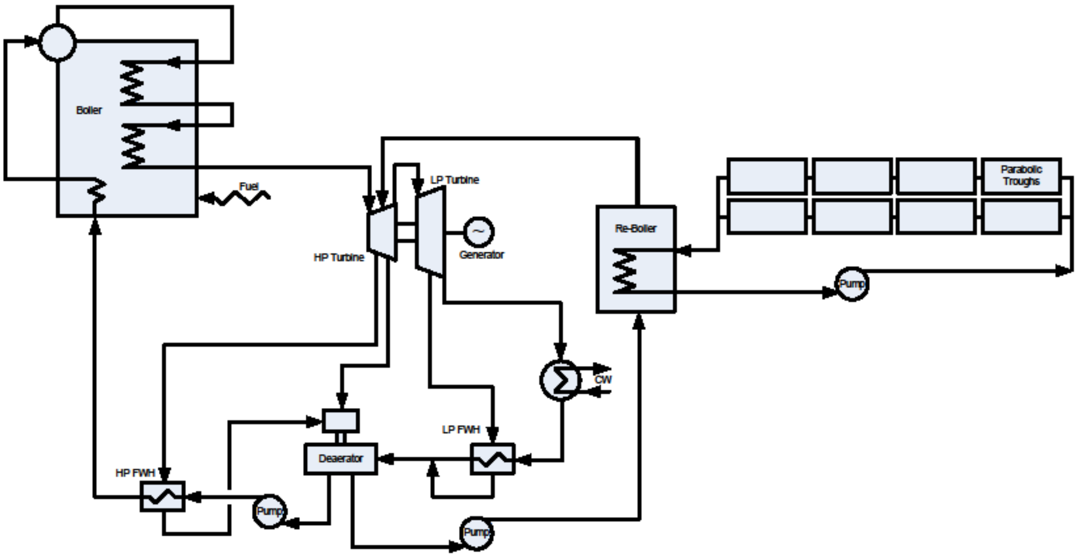

Figure 1. Simplified configuration of coal-fired boiler and integrated solar collectors.

5. Design Parameters

5.1 Plant Availability

It was assumed that the solar field is in full operation 30% of the time, and contributes 20 MWe of total plant generation. This accounts for overcast and diurnal conditions as thermal storage has not been considered in this study. Meanwhile, the coal-fired plant was based on 92% availability.

5.2 Climatic Data

Meteorological data used in the conceptual design is for a Central Queensland location. The Central Queensland region is home to major mining and industrial activities and hosts Australia's largest coal reserve. The climatic conditions utilized are characterized as sub-tropical to tropical and collected from the Bowen Airport Weather Station (1987-2009 as obtained from the Bureau of Meteorology) [Bureau of Meteorology, 2009]. The key climatic parameters are summarized in Table 1.

Table 1. Annual mean climatic conditions.

Parameter	Unit	Value
Maximum temperature	°C	28.6
Minimum temperature	°C	19.5
Relative humidity (9:00AM)	%	72
Relative humidity (3:00PM)	%	61
Rainfall	mm	831.6
Evaporation	mm	1,700
Daily sunshine	hours	8.3
Daily solar exposure	MJ/m^2	21.7

5.3 Coal Fuel Characteristics

Mass and energy balances are based on the following assumptions:

- Coal gross calorific value is 22.0 MJ/kg (as received);
- Coal quality assumed to constitute 49% fixed carbon, 17% ash, 22% volatiles and 12% moisture, on an as received basis;
- Coal contains 84.8% carbon, 4.9% hydrogen, 1.9% nitrogen, 0.6% sulphur and 7% oxygen, on an as received basis;
- No sulphur inherent in volatiles in coal;
- Content of unburnt carbon in ash is 4%;
- Average bed temperature in the circulating fluidized bed (CFB) boilers is 850°C;
- Limestone injected into the circulating fluidized bed, (CFB) boilers to remove 98% of SO_2 generated; and
- Coal combustion excess air is 20%.

5.4 Sorbent Characteristics

The constituents of the limestone used as sorbent are 94.5% calcium carbonate ($CaCO_3$), 0.8% magnesium carbonate ($MgCO_3$), 4.2% inert and 0.5% moisture.

5.5 Commodity Prices

Base prices used for the cost estimation are listed in Table 2.

Table 2. Commodity Prices in Australian Dollars (2009 data).

Commodity	Unit	Price
Coal	AU$/GJ	3.80
Treated water for boiler-make up	AU$/ML	740.00
Raw water for cooling tower make-up	AU$/ML	400.00
Limestone	AU$/t	107.00

6. Model Development

Computer-based modeling using Thermoflow package simulator delivers mass and energy balances, indicating that the cycle can be an integration of a coal boiler and an induction steam turbine generator with superheated steam from the solar system at 370°C at 29 bar.

The simple cycle coal boiler and steam turbine generator (STG) will be sized to produce 100MWe. The solar system will have the capacity equivalent to produce 20% of the required power output. When integrated and under optimum solar conditions the system will produce 100 t/h of superheated steam equivalent to displacing 20% of the coal consumption, hence, an equivalent CO_2 displacement. If the solar system is not used, the coal consumption will be increased to design conditions required to produce 100MWe. Therefore, the required electrical output is always satisfied.

7. Results

7.1 Inputs and Outputs

Mass and energy balances conducted on the basis of a 92% capacity factor for the coal plant and 30% capacity factor for the solar plant are presented in Table 3. At an equivalent power output, it is demonstrated that apart from reducing consumption of raw materials (i.e. coal and limestone), the solar/coal hybrid system generates less ash, minimizing waste emissions.

Table 3. Summary of modeling results.

Description	Unit	Coal	Solar/Coal
Net power output	MWe	100	100
Net annual power generation	GWh/yr	804.31	804.31
Coal consumption	t/yr	325,511	300,177
Limestone usage	t/yr	12,871	11,869
Bottom ash flow	t/yr	13,749	12,679
Fly ash flow	t/yr	32,051	29,555

7.2 CO_2 Emissions

Table 4 summarizes annual CO_2 emissions for the two cases, where emissions associated with the transportation of coal and limestone to site are also included. As shown, the emission factors for the base case and the hybrid case are 1.07 and 0.99 t-CO_2/MWh respectively. Further, the solar plant leads to corresponding CO_2 saving of 67,713 t-CO_2 annually, which is equivalent to 7.8% reduction in CO_2 from the coal base.

Table 4. Annual CO_2 emissions and emission factors.

Case	CO_2 Emission (t/y)			t-CO_2/MWh	Saving
	Coal Boiler Stack	Coal & Limestone Transportation	Total t-CO_2/y		t-CO_2/y
Coal	835,376	27,567	862,944	1.07	-
Solar/Coal	770,349	25,422	795,771	0.99	67,713

7.3 Economic Indicators

Economic evaluation incorporated capital, operating, maintenance and fuel costs, carbon tax, REC's, as well as possible government contributions towards renewable energy. The Net Present Cost (NPC) was calculated for each option based on a 30-year lifecycle from 2012 to 2041, assuming that construction begins in 2012. Capital costs included contingency to account for high uncertainty associated with requirements and costing of coal plant components. The NPC is evaluated by assuming a discount rate of 8% and an annual escalation of 3%. All monetary values in the analysis are given in Australian Dollars (AU$).

Table 5 presents the capital, annual operating and maintenance cost, fuel costs, carbon tax expenses and REC's credit in the year of 2016 (first full year in operation). While the capital cost for hybrid plant is substantially higher, the addition of the solar component into the coal plant results in lower annual costs related to operating and maintenance, fuel consumption and carbon tax as a result of decreased raw materials usage and waste emissions [Allani et al., 1997].

Furthermore, the impact of varying carbon tax from \$10/t-CO_2 increasing to \$50/t-CO_2 is examined. For both cases, the effect of increasing carbon tax beyond \$30/t-CO_2 was shown to exceed annual fuel costs. Carbon tax is thus a significant factor in the NPC analysis, considering that a typical coal-fired plants fuel costs makes up 60% of plant lifecycle cost.

Table 5. Costs for NPC analysis.

Description	**Unit**	**Cost**	
		Coal	**Solar/Coal**
Total Capital Cost	AU$ million	266.38	370.05
Operating & Maintenance Cost	AU$ million/yr	14.99	14.00
Fuel Consumption Cost	AU$ million/yr	30.35	27.99
Carbon Tax at \$10/t-CO_2	AU$ million/yr	10.61	9.79
Carbon Tax at \$20/t-CO_2	AU$ million/yr	21.23	19.57
Carbon Tax at \$30/t-CO_2	AU$ million/yr	31.84	29.36
Carbon Tax at \$40/t-CO_2	AU$ million/yr	42.45	39.15
Carbon Tax at \$50/t-CO_2	AU$ million/yr	53.07	48.93
REC’s (credit) at $40/MWh	AU$ million/yr	0	(2.60)

Note: Operating & Maintenance, Fuel Consumption, Carbon Tax and REC’s at 2016 Level.

As a part of the commitment to combat climate change, the Australian Government has recently allocated various grants towards the implementation of renewable energy. Apart from the solar/coal hybrid versus coal case, three additional scenarios have therefore been considered which include government grants in the order of $25 million, $50 million and $100 million respectively (corresponding to approximately 25%, 50% and 100% of the solar facility cost).

Table 6 shows NPC values at different carbon taxes. As shown, the effect of increasing carbon tax is more prominent in the coal-fired base case rather than the hybrid system. As the carbon tax increases, the cost gap between the hybrid and coal options diminishes.

Table 6. NPC at various carbon tax values.

Case	Net Present Cost (AU$ Million)					
	$\$0/t\text{-}CO_2$	$\$10/t\text{-}CO_2$	$\$20/t\text{-}CO_2$	$\$30/t\text{-}CO_2$	$\$40/t\text{-}CO_2$	$\$50/t\text{-}CO_2$
Coal	783.93	907.39	1,030.85	1,154.31	1,277.77	1,401.23
Solar/Coal	864.41	978.26	1,092.11	1,205.96	1,319.81	1,433.66
Solar/Coal (+ AU$ 25 million grant)	839.41	953.26	1,067.11	1,180.96	1,294.81	1,408.66
Solar/Coal (+ AU$ 50 million grant)	814.41	928.26	1,042.11	1,155.96	1,269.81	1,383.66
Solar/Coal (+ AU$ 100 million grant)	764.41	879.26	992.11	1,105.96	1,219.81	1,333.66

Table 7 compares electricity costs at different carbon tax scenarios. In the absence of a carbon tax scheme, the electricity produced from the base coal plant costs $87.56/MWh. This increases by $12.79/MWh for every $10/t-$CO_2$ increase in carbon tax. At $50/t-$CO_2$, electricity production costs $151.49/MWh – an increase of 73% from the base case with no carbon tax. In contrast, without a carbon tax consideration the cost of electricity production in the hybrid plant is $94.76/MWh. Although this is higher than the coal base, its volatility is reduced as carbon tax rises. For every $10/t-$CO_2$ increase in carbon tax, the electricity cost is predicted to increase by $11.79/MWh. The estimated cost to produce electricity at $50/t-$CO_2$ is $153.72/MWh – a 62% increase above the no carbon tax scenario.

Further, it is seen that electricity costs decreased as a result of direct governmental contribution. With the provision of a $25 million grant (~25% of solar facility cost), the electricity cost of the hybrid option would be at the same level as the coal base given a carbon tax of $40/t-$CO_2$ is enforced, or $7/t-$CO_2$ for a $50 million grant (~50% of solar facility cost). Increasing the contribution to $100 million (~100% of solar facility cost) further lowers the electricity cost to a level competitive against the coal option, even in the absence of carbon tax scheme.

Figure 2 provides an illustration on the impact of carbon price and solar subsidy on the price of electricity.

Table 7. Electricity cost at various carbon tax values.

Case	Electricity Cost (AU\$/MWh)					
	\$0/t-CO_2	**\$10/t-CO_2**	**\$20/t-CO_2**	**\$30/t-CO_2**	**\$40/t-CO_2**	**\$50/t-CO_2**
Coal	87.56	100.34	113.13	125.91	138.70	151.49
Solar/Coal	94.76	106.55	118.34	130.13	141.92	153.72
Solar/Coal (+ AU\$ 25 million grant)	91.47	103.26	115.05	126.84	138.63	150.42
Solar/Coal (+ AU\$ 50 million grant)	88.18	99.97	111.76	123.55	135.34	147.13
Solar/Coal (+ AU\$ 100 million grant)	81.61	93.40	105.19	116.98	128.77	140.56

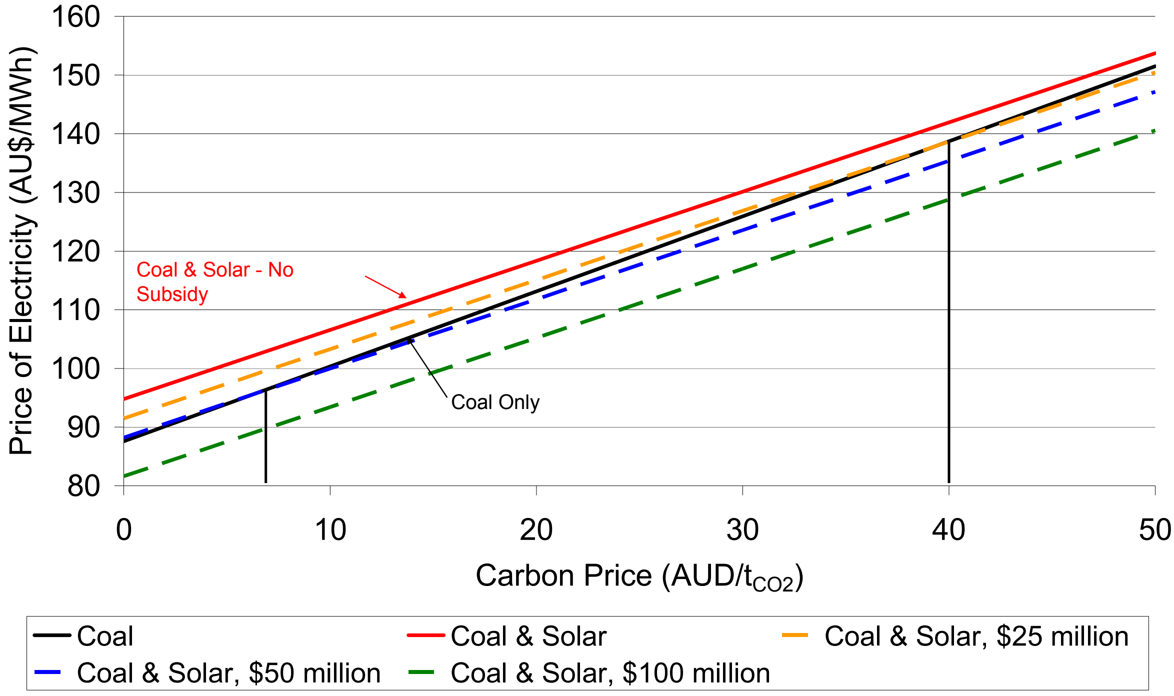

Figure 2. Impact of carbon price and solar subsidy on the price of electricity.

8. Conclusions

The current case study employs a unique combination of well-proven, established technologies (parabolic trough solar collectors and CFB boilers) into a single design to produce cleaner electrical power. Such integration provides electricity with reduced GHG emissions relative to conventional coal-burning plants.

While capital cost is currently the major hurdle, this study demonstrates that based on operating costs and emissions reductions such hybrid systems are very attractive. Also, carbon tax, to be in effect in Australia in a short-term, improves the economics of solar/coal hybrid over conventional coal-fired designs. However, its application requires a specific analysis to evaluate the climate conditions favorable to the application of the solar trough collectors to optimize its output.

The scenario suggesting incorporation of government funding in the order of $25 million shows that the coal/solar plant is competitive against the coal base system when carbon tax is >$40/t-$CO_2$. A higher grant of $50 million would justify the hybrid option at an even lower carbon tax of >$7/t-$CO_2$. While the capital cost of the solar plant is estimated as ~$104 million, the addition of $100 million funding into the project would be adequate to position the coal/solar system as the preferred option over the coal system regardless of carbon price level.

Further, it is observed that the solar heating contributes lower annual power production than rated capacity due to time-dependent availability of solar energy, thus underutilizing the higher capital investment of the solar system overall [Seyedan and Hynes, 2004; Seyedan and Hynes, 2007]. Consequently, it raises the opportunity for optimizing the benefits of the solar system by addition of a thermal storage system, enabling dispatch of stored energy based on demand and not production [Herrmann et al., 2004]. Further, the higher solar capacity factor arising from the installation of a storage system reduces the impact of an increase in carbon tax value.

9. References

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