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An Enviro-Economic Comparison of Two Different CO_2 Avoidance Processes for NGCC-Derived Electricity

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In order to combat the rising carbon dioxide emission level several technologies have been proposed to deal with the challenge. This paper compares the economic and emission performance of two gas turbine based technologies: integration with solar thermal energy (STE) and post combustion carbon capture and storage (CCS). Both technologies are integrated into a natural gas combined cycle (NGCC) power plant. The comparison is presented using a multi-objective optimisation (MOO) framework to provide the trade-offs between the increased plant CO_2 equivalent (CO_{2e}) emission reduction and economic performance for both cases. This has been performed using a dynamic optimisation methodology enabling the calculation of the net present value of the power plants including real electricity price data along with the variable solar radiation. The economic impacts of CO_2 pricing and government co-investment are also analysed to determine the required assistance to achieve the economic breakeven point.

1. Introduction

In order to address the growing problem of climate change, it will be insufficient to swap coal to gas fired power to meet the 2 °C temperature rise scenario (IEA, 2012). In order to reduce the emissions of NGCC different process modifications have been suggested. The two processes studied here are carbon capture and storage (CCS) and the solar thermal energy (STE). Both of these processes are integrated into an NGCC power plant.

The addition of CCS is detrimental to the plant's economic performance. Alongside the capital investment and associated capture plant operating cost, CCS reduces the electrical output from the power plant. The most commercially ready process for CCS is solvent absorption where CO_2 is absorbed from the flue gas into a solvent. The solvent is then regenerated, requiring energy input. One method of defining this energy reduction is with the energy penalty (ΔE), defined as:

$$\Delta E = \frac{P_{w/ocap} - P_{wcap}}{P_{w/ocap}} \% \tag{1}$$

where $P_{w/o\ cap}$ and P_{cap} are the power plant outputs without and with capture. Sipöcz et al. (2011) shows a ΔE of 14.5 % at a capture rate of 90 %. Exhaust gas recirculation (EGR), where a portion of the flue gas is recycled to the gas turbine air inlet to increase the CO_2, which reduces the energy penalty to 12.0 % (Sipöcz et al., 2011). ElKady et al. (2009) showed the maximum EGR possible without gas turbine modifications was 35 %. The most commonly used solvent for post-combustion capture (PCC), monoethanolamine (MEA), has been shown by Supap et al. (2006) to degrade in the presence of oxygen. As a result potassium carbonate (K_2CO_3), similar to that used by Pandit et al (2014), is used for this study.

Solar thermal energy integration has also been studied as a method of reducing the emissions from gas turbine power plants. The SOLGATE project (European Commission, 2005) looked at the use of solar thermal energy to preheat the combustion air prior to entering the combustion chamber. This process has been further developed by the SOLUGAS project (Krozynietz et al, 2012). Spelling et al (2012) have investigated the trade-offs between levelised cost of electricity (LCOE) and investment costs of solar

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assisted NGCC power plants. As with carbon capture the addition of solar thermal energy requires significant capital investment, and additional operating costs.

With two different processes, and the competing objectives of economic and environmental performance, multi-objective optimisation (MOO) is used for the optimisation. MOO allows for the optimisation of two or more variables at the same time allowing for the comparison of different cases on both economic and environmental benefits. The MOO results in a Pareto-optimal front show the optimised performance of the power plants over all allowable operating conditions. Similar to Kang et al. (2014), real electricity price data is used to determine the power plant performance over the whole year.

2. Methodology

The power plant and capture process were modelled within the commercial process modelling software Aspen Plus® V8.4. The Heat Integration and steam cycle process optimisation was calculated from the Grand Composite Curve as in work by Harkin et al. (2012). The gas turbine used as the basis for both processes is the Alstom GT26 (Alstom, 2007). The gas turbine power plant performance is given in Table 1.

The focus in this paper is the comparison between the CO_2 reducing process of CCS and STE integration. In the case of CCS the solvent absorption process is modelled with steam extraction from the steam turbine used to provide the energy for solvent regeneration. The captured CO_2 is then compressed to 100 bar(a) for storage. For the solar thermal assisted case the solar tower is modelled using a heater to provide the energy to the compressed air. The amount of energy provided to the heat is given by solar field size and efficiencies. The two processes which are optimised are shown in Figure 1, and performance parameters are given in Table 2.

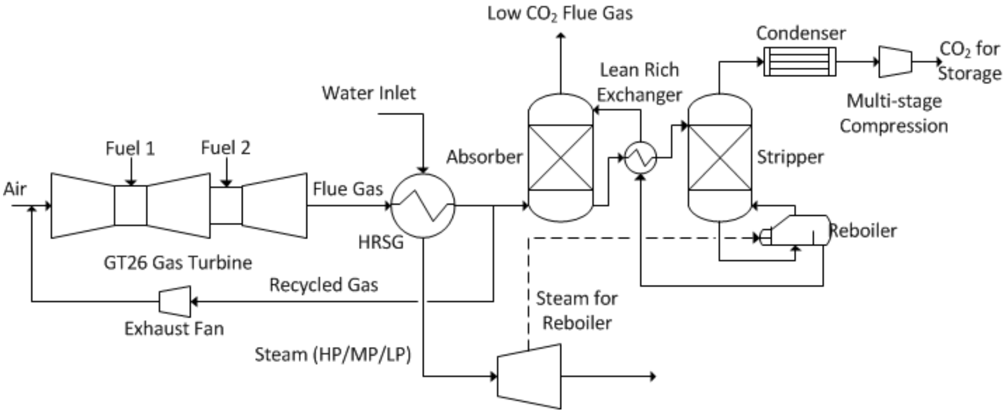
The Aspen Plus® models were used to generate surrogate models of the processes in order to improve computation time. The surrogate model was created using the SUMO software toolbox (Gorissen et al. 2010) using artificial neural networks. The SUMO generates a set of empirical formulas that can then be used to calculate the process performance and this reduces the total CPU time required for the multiple simulations required in the MOO framework. A comparison of the surrogate model performance to the Aspen Plus® simulation for the NGCC CCS process is shown in Figure 2.

The MOO used in the optimisation is the Genetic Algorithm based code NSGA-II developed by Deb et al. (2002), which Sharma et al. (2012) have adapted to operate in VBA through Microsoft Excel®. NSGA-II has been applied to CO_2 reduction by Li Yuen Fong et al (2014) and Sharma et al. (2014). The competing values of economic performance, defined by the Net Present Value (NPV), and the environmental performance, defined by the reduction in CO_2 emissions, will be optimised using the MOO.

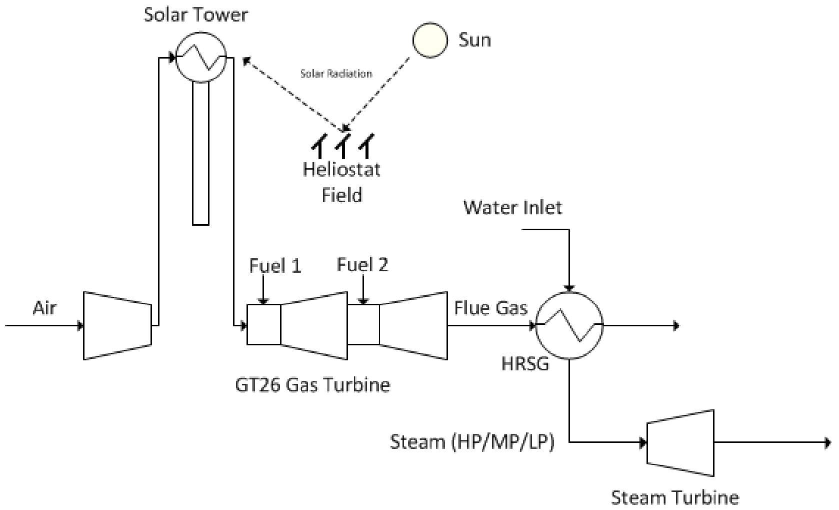
First defined by Ho et al. (2009) the economic parameters are given as part of Table 2. In line with Pandit et al. (2014), economic performance is calculated in 2011 Australian dollars ($AU). The South Australian electricity prices are taken from the 2013 - 14 financial year (AEMO, 2014). During this economic period Australia had a carbon price of 24.15 AU/tCO_{2e} and this has been included in the economic analysis. 2011 - 12 financial year data, inflated to 2013 - 14, has also been used to compare the effect of the use of a carbon price. Three carbon prices are analysed 0, 24.15 and 50 AU/tCO_2 along with a government co-investment of 50 % on the carbon emission reduction equipment. This co-investment affects the carbon capture plant and solar thermal equipment, but not the base NGCC plant.

Table 1: Alstom GT26 combined cycle power plant performance (Alstom, 2007)

Natural Gas Combined Cycle	
Gas Turbine (GT) ISO Rating (MW)	288
GT Exhaust Gas Flow (kg/s)	650
GT Exhaust Gas Temperature (°C)	614
Steam Turbine Power Output (MW)	157
Steam Turbine HP Pressure/Temperature (bar/°C)	135.3/565
Steam Turbine MP Pressure/Temperature (bar/°C)	28/565
Steam Turbine LP Pressure/Temperature (bar/°C)	4.74/287



(a) NGCC with Post-Combustion Carbon Capture



(b) Solar thermal assisted NGCC

Figure 1: Basic process diagrams for the two processes studied, (a) NGCC power plant with solvent absorption post-combustion carbon capture, and (b) solar thermal assisted NGCC power plant

The dynamics of the solar irradiance and electricity prices are handled using a statistical approach. Rather than model each 8,760 h individually a frequency distribution of the solar and electricity data is used to determine the power plant performance as well as costs and revenue over the whole year. Real solar and electricity data is used where available. The calculations are performed by integrating across the price and solar ranges to determine overall plant performance. In the solar assisted NGCC power plant, for each solar irradiance level the power output of the plant is calculated, along with the expected value of the electricity produced.

Table 2: Process and economic performance parameters. Solar efficiency data from Xu et al. (2011)

Solar Plant Data			
Location	Port Augusta, South Australia	Type	Solar Tower
Maximum Temperature (°C)	950	Pressure drop (kPa)	30
Field Efficiency (%)	75	Receiver Efficiency (%)	90
Economic Data			
Discount Rate (%)	7	Load Factor (%)	90
Project Lifetime (y)	25	Natural Gas Price ($AU/GJ)	4
Build Time (y)	2	Carbon Prices (AU/tCO_{2e}$)	0, 24.15, 50
CO_2 Storage Cost (AU/tCO_{2e}$)	6.03	Government Co-investment (%)	0, 50

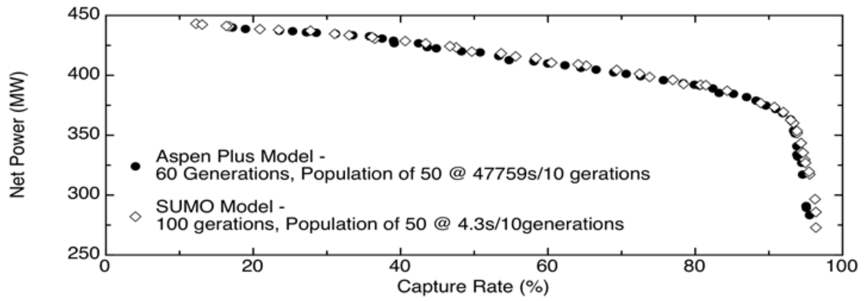


Figure 2: Comparison of the NGCC CCS plant surrogate model to the Aspen Plus® model. Number of generations and simulation CPU time is shown

The expected value, *EV*, is defined as:

$$EV = \int x \times p(x)dx \tag{2}$$

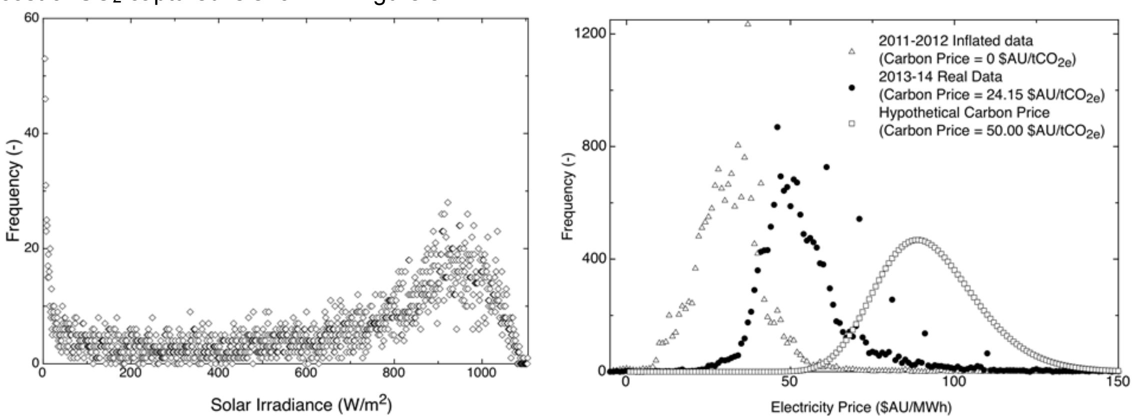
where x is the electricity price and *p(x)* is the probability of that price.

Real solar and electricity data is used where available, and numerical integration is used. The solar irradiance distribution for Port Augusta, South Australia is shown in Figure 3, along with the electricity price data for South Australia. The electricity price data shows three price distributions based on the carbon price. Real 2013-14 financial year data, with a carbon price of 24.15 $\$AU/tCO_{2e}$ is shown along with zero carbon price data from the 2011-12 data inflated to 2013-14 prices and a 50 $\$AU/tCO_{2e}$ hypothetical data set modelled with a log-normal distribution.

Comparing the real data from 2013-14 to the inflated data from 2011-12 shows an increase in average electricity price of 29.92 $AU/MWh (61.71 $AU/MWh in 2013-14 to 31.79 $AU/MWh for the inflated data). This gives an average electricity price increase of 1.24 $AU/MWh per 1 $\$AU/tCO_{2e}$. This is then used to create the hypothetical carbon price cases. For a carbon price of 50 $\$AU/tCO_{2e}$ this results in an estimated average electricity price of 93.74 $AU/MWh.

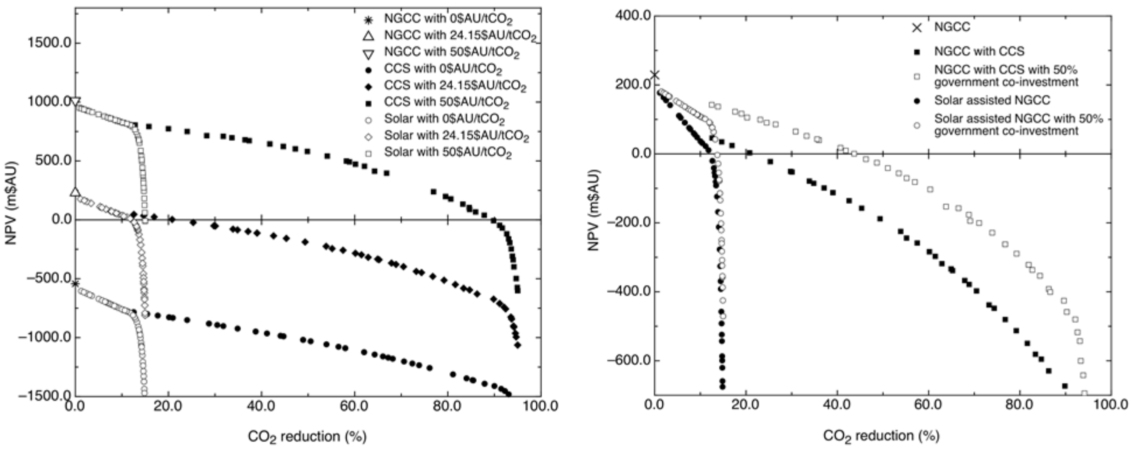
3. Results

Results of the different scenarios are given in Figure 4. Figure 4 (a) shows the effect of changing the carbon price of 0 $\$AU/tCO_2$, 24.15 $\$AU/tCO_2$ and 50 $\$AU/tCO_2$. Figure 4 (b) shows the effect of a 50 % government co-investment on the CO_2 reduction equipment, i.e. the carbon capture and solar thermal plants. Solar assisted NGCC power plants cannot achieve more than around 15 % CO_2 reduction as the amount of potential energy from the solar field that can be harnessed by the NGCC plant is reduced. The cost of CO_2 captured is shown in Figure 5.



(a) (b)

Figure 3: Frequency plots used with (a) solar irradiance (bin size = 1 W/m^2), and (b) electricity price data (bin size = 1 $AU/MWh), including three carbon price cases



(a) *(b)*

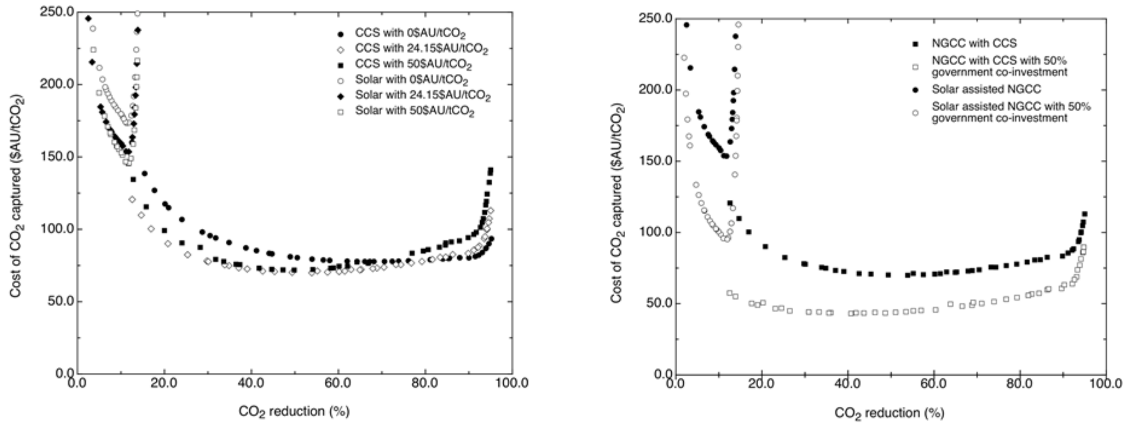
Figure 4: Net Present Value (NPV) for all cases with (a) comparing the effect of carbon price, and (b) government co-investment. Base NGCC performance is shown at 0 % CO_2 reduction

4. Discussion

Increasing the carbon price increases the NPV of all cases, as the emission intensity of all plants is lower than the increase in electricity price compared to the carbon price increase. The increase in average electricity price corresponds to an increase comparable to brown coal power plant emission intensities of around 1.24 tCO_2/MWh. As a result the increase in the electricity price, means that the electricity produced is more valuable than reducing CO_2 emissions for NGCC power plants. The base NGCC has an emission intensity of 0.34 tCO_2/MWh.

A government co-investment also improves the NPV performance of both cases as the capital expenditure is reduced. The effect of the reduced capital requirement is greater at higher capture rates where the amount of additional capital has a higher cost, and hence reducing the cost has a greater impact.

Above solar field areas of around 600,000 m^2 the amount of extra energy usable in the GT is reduced and the extra field size offers reduced impact as most of the energy cannot be utilised. As the energy cannot be used the cost of maintaining the equipment exceeds the savings in natural gas and carbon price, increasing the cost of the solar assisted cases further. This leads to the drop in NPV at a 15 % CO_2 reduction.



(a) *(b)*

Figure 5: Cost of CO_2 captured for each of the cases: (a) carbon price cases, and (b) government co-investment. Cost of CO_2 captured calculated by ΔNPV/Σ Discounted CO_2 Reduced reduction level.

5. Conclusions

Using a statistical approach, dynamic MOO was performed on two different technologies for reducing NGCC based power plant CO_2 emissions. Using real electricity price and solar irradiance data carbon capture and storage and solar thermal energy were assessed based on economic and emission reduction potential. At most CO_2 reduction level the CCS cases outperformed the solar assisted cases. However, even with co-investment, there is still a significant cost associated with reducing CO_2 emissions.

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