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A techno-economic analysis of the application of continuous staged-combustion and flameless oxidation to the combustor design in gas turbines

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Abstract

The impact of NO_x reduction technologies upon a gas turbine power station has been investigated using the ECLIPSE process simulator. Technical, environmental and economic assessments were performed, based upon a model of the simple cycle gas turbine, fuelled by natural gas.

The technologies assessed were: a) selective catalytic reduction (SCR); b) continuous staged air combustion (COSTAIR); and c) flameless oxidation method (FLOX).

The SCR method produced a 90% reduction of NO_x emissions, at an additional penalty to the electricity cost of 0.19–0.20 p/kWh, over the base case of simple cycle with standard combustor.

The COSTAIR method reduced 80.4% of NO_x emissions, at an additional electricity cost of 0.03–0.04 p/kWh, over the base case; but 0.16–0.17 p/kWh less than the SCR method at a slightly higher level of NO_x emissions.

The FLOX method generated 92.3% less of NO_x emissions, at an additional electricity cost of 0.08–0.11 p/kWh, over the base case; but 0.09–0.11 p/kWh less than the SCR method at a lower level of NO_x emissions.

A sensitivity analysis of the Break-Even Selling Price (BESP) of electricity and the Specific Investment (SI) versus the cost of different burner systems shows that the SCR system had the highest values for BESP and SI; and the COSTAIR system had the lowest.

The results show that the use of these non-standard burners could offer an effective method of reducing NO_x emissions considerably for simple cycle gas turbine power plants with minimal effect on system capital cost and electricity selling price, and were also cheaper than using SCR.

Keywords: Combustion; NO_x emissions; Combustor design; Techno-economic analysis

1. Introduction

In power generations the combustion of fossil fuels in the furnace or gas turbines contributes significantly to the emissions of nitrogen oxides (NO_x) [1], i.e. NO, NO_2 and N_2O. NO_x emissions are considered a major pollutant of the atmosphere, and N_2O is said to be a major contributor to climate change. In addition, NO and NO_2 are believed to play a major role in the formation of ground level ozone, photochemical smog and acid rain, etc [2]. Increasingly stringent regulatory requirements provide the impetus for the development and use of advanced technologies to reduce air pollutant emissions, including NO_x.

The NO_x emitted from gas turbines come from two sources — thermal and fuel NO_x [2,3]. In each case, nitrogen and oxygen present in the combustion process combine to form NO_x. Thermal NO_x is formed by the dissociation of atmospheric nitrogen (N_2) and oxygen (O_2) in the turbine combustor and the subsequent formation of NO_x. When fuels containing nitrogen are combusted, this additional source of nitrogen results in fuel NO_x formation. Because most turbine installations burn natural

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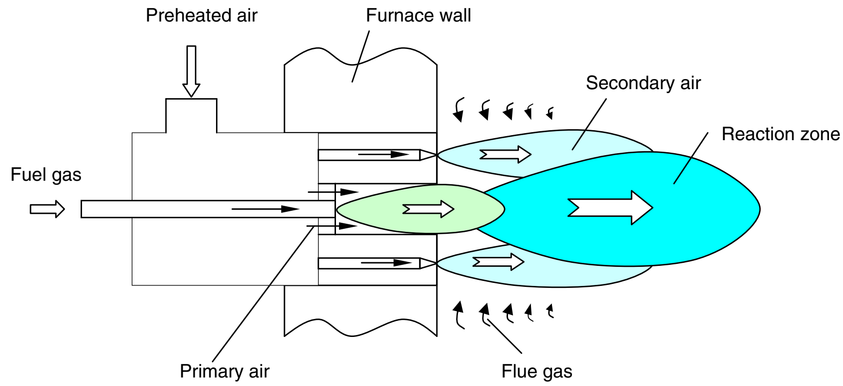

Fig. 1. Continuous staged air combustion burner.

gas with little or no nitrogen content, thermal NO_x is the dominant source of NO_x emissions.

The power output of a gas turbine is directly related to the firing temperature, which is directly related to flame temperature. But the rate of thermal NO_x formation is also directly related to flame temperature. The formation of NO_x increases exponentially with increases in temperature and increases dramatically when the temperature exceeds 1590 °C on natural gas [3–5].

Conventional simple cycle gas turbine power generation technology with a standard combustor, generates high NO_x emissions which would exceed projected European NO_x emission regulations [2,4,6]. Therefore, additional NO_x reduction technologies are required. NO_x emissions can be controlled in two ways: during combustion or after combustion. Post-combustion techniques, such as SCR [7], reduce NO_x emissions after they formed and are more expensive. So the during-combustion methods, which prevent NO_x from forming in the first place, are usually pursued.

The continuous staged air combustion (COSTAIR) [8–10] and flameless oxidation (FLOX) [9–12] are new combustion technologies, which reduce the combustion temperature in a combustion chamber, result in low NO_x formation in the combustion process and emit less NO_x emissions.

The objective of this study is to investigate the techno-economic feasibility of applying the technology of continuous staged air combustion or flameless oxidation to a simple gas turbine cycle, compared to that of conventional combustion technology.

2. The technologies of continuous staged air combustion and flameless oxidation

The description of the features of continuous staged air combustion and flameless oxidation can be found in the literatures [8–16]. The following section is a brief description of the burners applying these technologies.

2.1. Continuous staged air combustion

In the mode of continuous staged air combustion [8–11], as shown in Fig. 1, preheated air is divided into two parts, primary air and secondary air, to mix with the fuel at two different points. The heat is released more uniformly throughout the combustion chamber, this results in lower NO_x formation notably. Fig. 1 shows a two-stage burner. The secondary air is injected directly into the combustion chamber, flue gas is recirculated (FGR) and this enhances the NO_x reduction effect. FGR reduces NO_x by reducing the peak temperature in the burner. By diluting the charge with inert gas, the adiabatic flame temperature is reduced. This has the opposite effect of increasing oxygen availability during combustion. The recirculated gas also reduces peak combustion temperature by absorbing some of the heat of combustion. Nitrogen oxides are known to form at high temperatures [8] and this reduction in temperature leads to decreased NO_x formation in the burner.

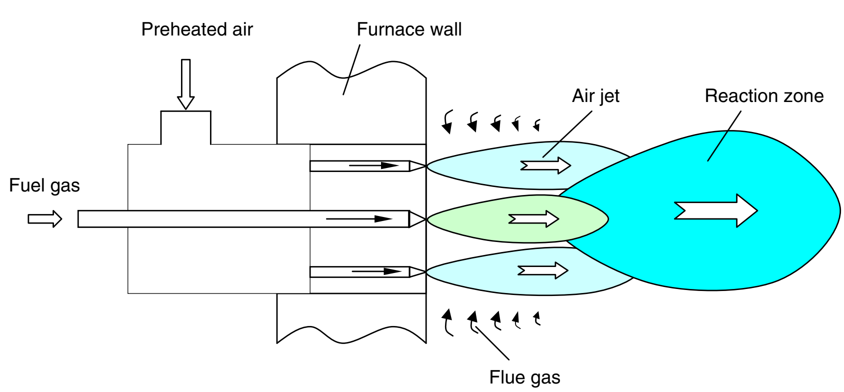

Fig. 2. Flameless oxidation burner.

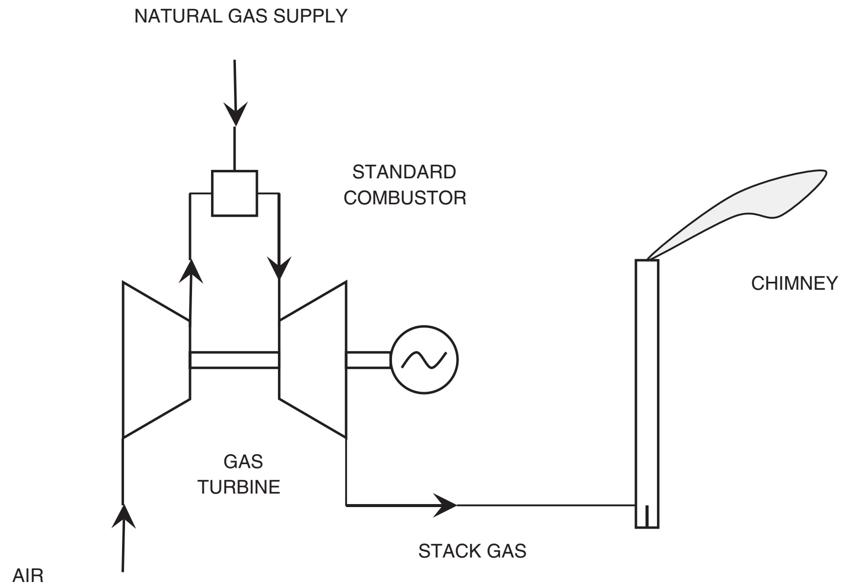

Fig. 3. Natural gas simple cycle gas turbine with standard combustor.

2.2. Flameless oxidation

In flameless oxidation mode [12–16], fuel and air are gradually mixed with large amounts of recirculated exhaust gas thereby reducing the adiabatic flame temperature of the mixture and heating up the air and fuel or air/fuel mixture at the same time. A flameless oxidation burner is shown in Fig. 2. The main feature of flameless oxidation is: no air is added to the fuel prior to injection. The energy required for ignition is provided by the recirculating flue gas. The furnace chamber temperature must be at least 800–900 °C. The recirculating flue gas should be mixed into the combustion air and into the fuel, or into the fuel air mixture. The amount of the recirculating flue gas should be large enough to offer the energy to ignite the fuel air mixture. For flameless oxidation, the fuel and the air are both injected directly into the furnace chamber. They react downstream from the point of injection. That leads to very low flame temperatures and low oxygen partial pressures in the reaction zone and as a result of this to a low thermal NO formation.

3. Process descriptions

The evaluated systems have all been based on the simple cycle gas turbine, which is described in reference [17]. Four processes are described in the following paragraphs. The processes are simulated using the software package of ECLIPSE.

3.1. A brief introduction of ECLIPSE

To provide a consistent basis for evaluation and comparison, the systems analysed are modelled using the ECLIPSE process simulation package [18–20]. ECLIPSE was developed for the European Commission and has been used by the Northern Ireland Centre for Energy Research and Technology at the

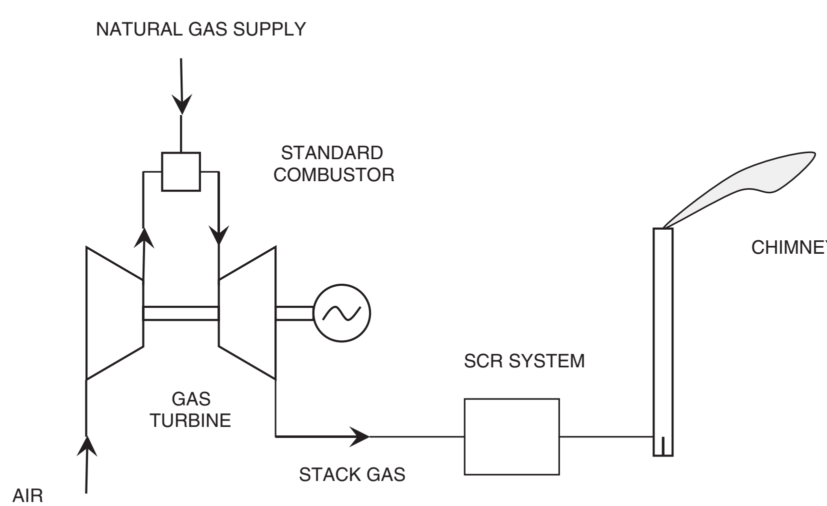

Fig. 4. Natural gas simple cycle gas turbine with SCR system.

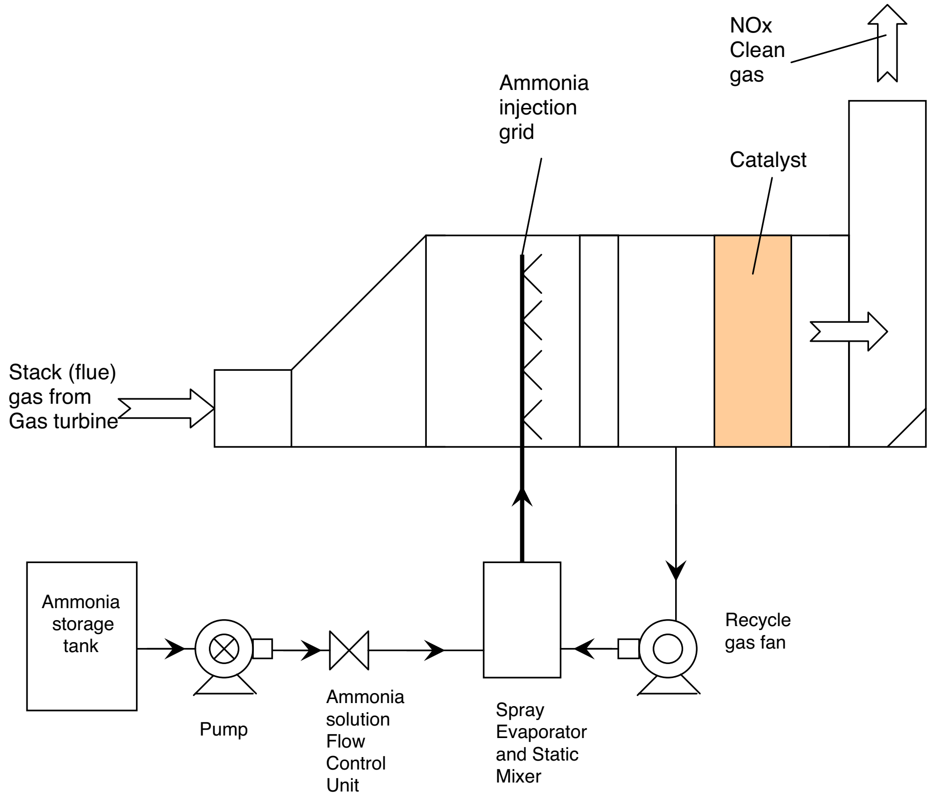

Fig. 5. Process flow diagram of selective catalyst reduction system.

University of Ulster since 1986 [21,22]. ECLIPSE is a personal-computer-based package containing all of the program modules necessary to complete rapid and reliable step-by-step technical, environmental and economic evaluations of chemical and allied processes. ECLIPSE uses generic chemical engineering equations and formulae and includes a high-accuracy steam-water thermodynamics package for steam cycle analysis. It has its own chemical industry capital costing program covering over 100 equipment types. The chemical compound properties database and the plant cost database can both be modified to allow new or conceptual processes to be evaluated. A techno-economic assessment study is carried out in stages; initially a process flow diagram is prepared, technical design data can then be added and a mass and energy balance completed. Consequently, the system's environmental impact is assessed, capital and operating costs are estimated and an economic analysis performed. Whilst every effort is made to validate the capital cost estimation data, using published information and actual quotations from equipment vendors, the absolute accuracy of this type of capital cost estimation procedure has been estimated

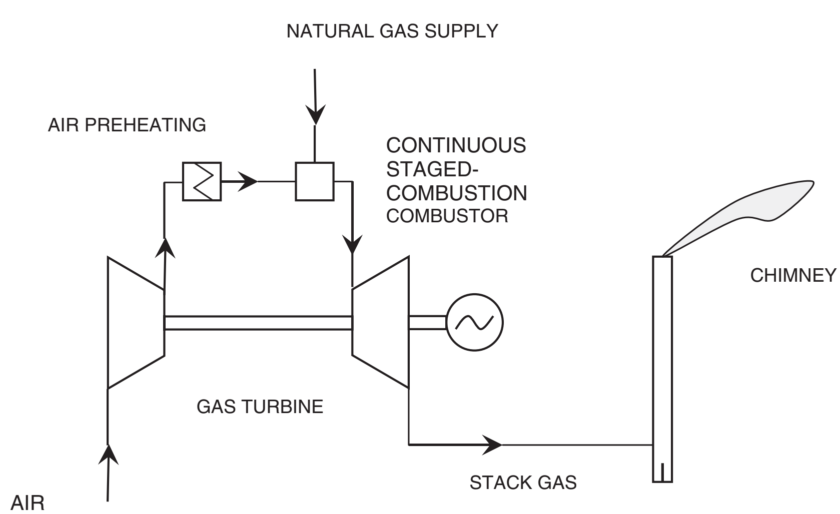

Fig. 6. Natural gas simple cycle gas turbine with continuous staged-combustion combustor.

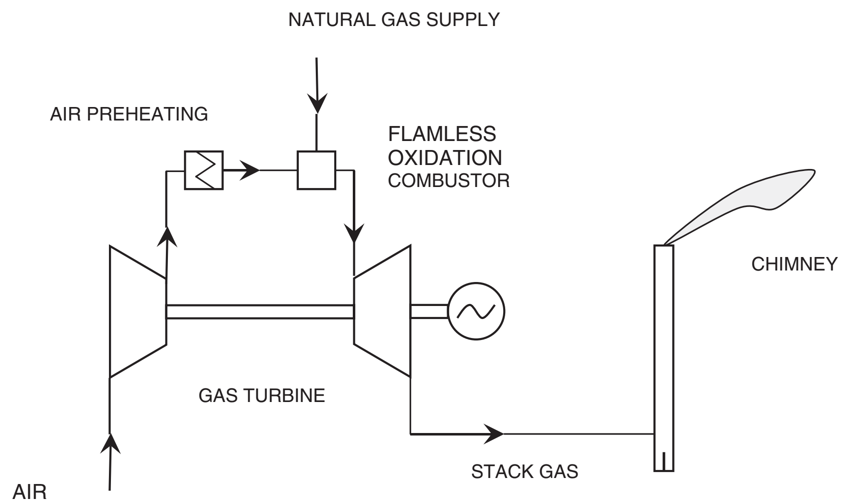

Fig. 7. Natural gas simple cycle gas turbine with flameless oxidation combustor.

at about 25–30%. However, as the comparative capital cost estimates are based on the accurate calculation by the mass and energy balance program of differences in basic design, families of similar technologies composed of similar types of equipment can be compared on a consistent basis.

Table 1
Technical and emission results

	Gas turbine (base case)	Gas turbine + SCR	Gas turbine + COSTAIR	Gas turbine + FLOX
Fuel flow (kg/s)	13.17	13.17	13.17	13.17
Inlet mass flow (kg/s)	602.7	602.7	602.7	602.7
Turbine inlet conditions				
(Pressure bar)	15.86	15.86	15.86	15.86
(Temperature °C)	1288	1288	1288	1288
Turbine outlet conditions				
(Pressure bar)	1.05	1.05	1.05	1.05
(Temperature °C)	566	566	547	519
Compressor polytropic				
Efficiency (%)	90.0	90.0	90.0	90.0
Turbine Polytropic				
Efficiency (%)	87.0	87.0	87.0	87.0
HHV (MJ/kg)	55.12	55.12	55.12	55.12
LHV (MJ/kg)	49.80	49.80	49.80	49.80
Thermal input (MW)				
(HHV)	726	726	726	726
(LHV)	656	656	656	656
Gas turbine power output (MWe)	434	434	426	413
Total power output (MWe)	221	221	219	215
NO_x emissions (mg/m^3) (5% O_2)	112	11.2	22	8.6
Auxiliary (MWe)		3		
Transformer losses (MWe)	1	1	1	1
Net electricity production (MWe)	220	217	218	214
Overall efficiency				
(%) (HHV)	30.3	29.9	30.0	29.5
(LHV)	33.5	33.1	33.2	32.7

3.2. Simple cycle gas turbine with standard combustor

The simple cycle gas turbine with standard combustor is shown in Fig. 3. Natural gas direct from the main gas pipeline is fed to the combustor of an industrial heavy duty gas turbine. Here the natural gas is burnt in air from the compressor stage and the resulting hot gases are expanded through the gas turbine. There is no heat recovery from the exhaust gases which are vented to the atmosphere via the stack. The NO_x emissions from this cycle are very high, because of the high flame temperature, the high oxygen concentration in the reaction zone.

3.3. Simple cycle gas turbine with standard combustor plus NO_x Selective Catalytic Reduction (SCR)

In order to reduce NO_x emissions from gas turbines with standard combustor, so that they comply with the strict environmental requirement, NO_x Selective Catalytic Reduction systems (SCR) have been used. The simple cycle gas turbine with standard combustor plus NO_x SCR is shown in Fig. 4. A Selective Catalyst Reduction System is shown in Fig. 5. The

Table 2
Economic results

Capital cost (in £ Million)	Gas turbine (base case)	Gas turbine + SCR	Gas turbine + COSTA	Gas turbine + FLOX
Building	3	3	3	3
Extra cost for the new combustor (burner)			0.2	0.2
Gas turbine with standard combustor	114	114	114	114
Selective catalytic reduction	0	9		
Total capital cost (TCC) in Million £	117	126	117.2	117.2
Specific investment (£/kWe)	533	580	538	547

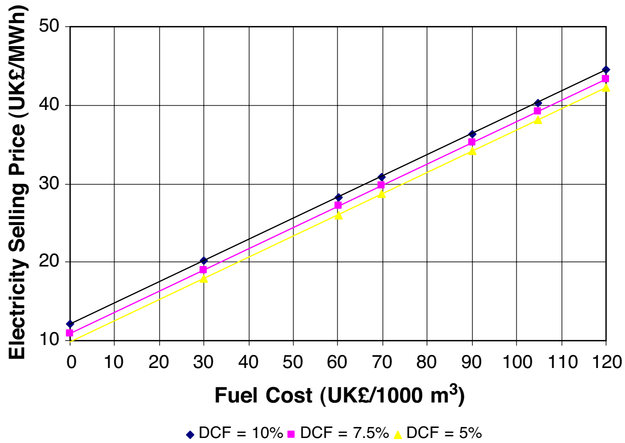

Fig. 8. Influence of fuel cost on break-even electricity selling price for simple cycle gas turbine.

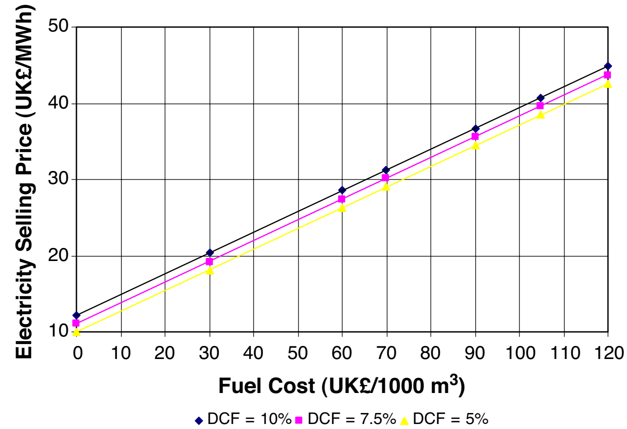

Fig. 10. Influence of fuel cost on break-even electricity selling price for simple cycle gas turbine with continuous staged air combustion chamber.

SCR technology is a post-combustion nitrogen oxides (NO_x) control technology capable of providing NO_x reductions > 90% [23,24].

With SCR, NO_x reductions are achieved by injecting ammonia into the flue gas, which then passes through layers of catalyst in a reactor. The ammonia and NO_x react on the surface of the catalyst, forming molecular nitrogen (N_2) and water. SCR has been applied mainly to electric utility boilers firing coal and natural gas. The reactions in the SCR system are as following:

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$$

As shown in Fig. 5, the SCR system uses ammonia injection into the process stream prior to this catalytic reaction. When molecules of NO_x, ammonia and oxygen simultaneously contact the "catalytic site", the SCR reaction takes place converting NO_x and ammonia to nitrogen and water vapour. In this way the flue gas is cleaned of NO_x. Only a trace amount (ppm) of NO_x and ammonia leaves via the system exhaust.

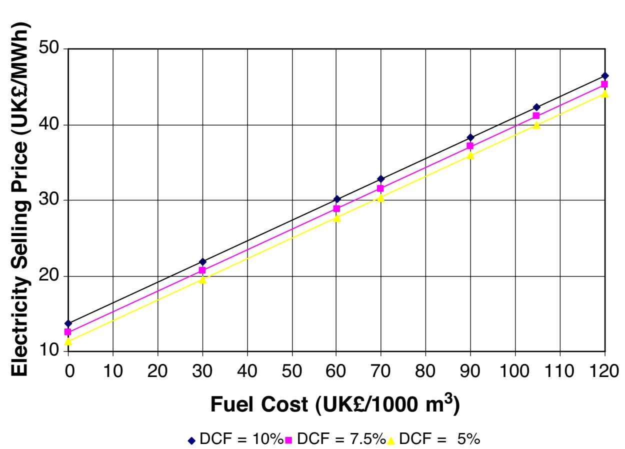

Fig. 9. Influence of fuel cost on break-even electricity selling price for simple cycle gas turbine + SCR.

3.4. Simple cycle gas turbine with continuous staged-combustion (COSTAIR) combustor

The simple cycle gas turbine with continuous staged-combustion combustor is shown in Fig. 6. The standard combustor is replaced by a continuous staged-combustion combustor. The other parts of the system remain the same as in the gas turbine with the standard combustor.

3.5. Simple cycle gas turbine with flameless oxidation (FLOX) combustor

The simple cycle gas turbine with flameless oxidation combustor is shown in Fig. 7. The standard combustor is replaced by a flameless oxidation combustor, while the other parts of the turbine system remain the same as in the gas turbine with the standard combustor.

4. Simulation results and discussion

The simulation takes the simple cycle gas turbine from Ref. [17] as the base case; the simulation of NO_x emissions is based

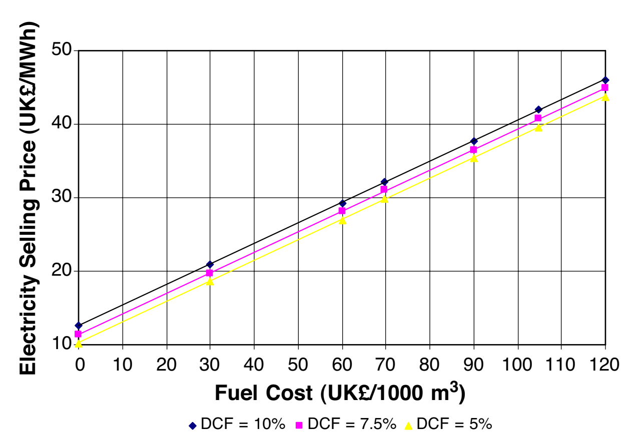

Fig. 11. Influence of fuel cost on break-even electricity selling price for simple cycle gas turbine with flameless oxidation combustor.

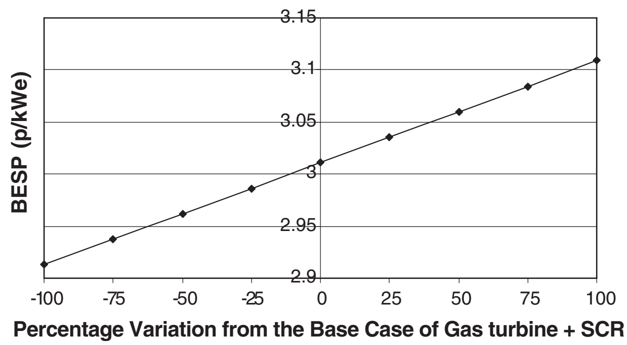

Fig. 12. Sensitivity of electricity selling price versus selective catalytic reduction system cost.

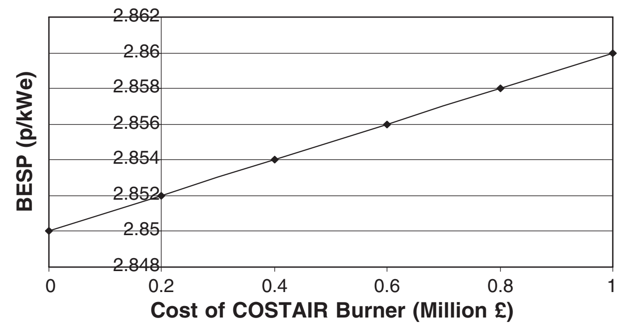

Fig. 14. Sensitivity of electricity selling price versus COSTAIR burner extra cost.

on the results from experimental studies on the COSTAIR and FLOX burners [10,11]. The technical and environmental results of the cases investigated are given in Table 1. The results determined during the economic analysis are displayed in Table 2 and Figs. 8–11. The discussion in the following assumes that the discounted cash flow rate (DCF) is 10% (and for comparisons, DCFs of 7.5% and 5% are shown).

4.1. The results of simple cycle gas turbine with standard combustor

The first columns in Tables 1 and 2 and Fig. 8 show the simulation results for the simple cycle gas turbine with standard combustor (burner). The thermal input is 656 MW at a lower heating value of the natural gas. The net electricity production was found to be 220 MWe and overall efficiency to be 33.5% at the lower heating value. For the base case, the capital cost of the gas turbine was 114 Million pounds and the building cost was 3 Million pounds [17], giving a specific investment of 533 pounds per kilowatts of electricity (£/kWe). When powered by natural gas [with a price of £1.72/GJ (£60/per 1000 m^3)], a break-even electricity selling price (BESP) of 2.83 p/kWh was found; with a natural gas price of £2.0/GJ (£69.8/per 1000 m^3), it gives a break-even electricity selling price of 3.10 p/kWh; and with a natural gas costing £3.0/GJ (£104.7/per 1000 m^3) gives a break-even electricity selling price of 4.03 p/kWh.

4.2. The results of simple cycle gas turbine with standard combustor plus SCR

Use of SCR system involves burning natural gas to raise the flue gas temperature to that required by the $deNO_x$ catalyst [1], thus increasing the thermal input. The auxiliary power requirement also rises due to the additional load on the induced draft fan. This reduces the net power production by 2.54 to 434 MWe and the efficiency from 33.5% to 33.1%, in terms of its lower heating value. The specific NO_x emissions are reduced from 112 to 11.2 mg/m^3 (5% O_2) [17,23]. The additional capital cost required for the SCR system was calculated at £9 M [23,24]. As shown in Figs. 8 and 9, with a natural gas price of £1.72/GJ (£60/per 1000 m^3), a break-even electricity selling price of 3.01 p/kWh is found; with a natural gas price of £2.0/GJ (£69.8/per 1000 m^3) there is a break-even electricity selling price of 3.28 p/kWh, which compares with the 3.10 p/kWh for the simple cycle gas turbine; with a natural gas costing £3.0/GJ (£104.7/per 1000 m^3) gives a break-even electricity selling price of 4.23 p/kWh compared with the base case of 4.03 p/kWh.

4.3. The results of simple cycle gas turbine with a COSTAIR combustor

The main change in the technical and environmental results for continuous staged air combustion is to supply air into the combustion chamber gradually. This results in slower combustion rate and then lower peak combustion temperature, and

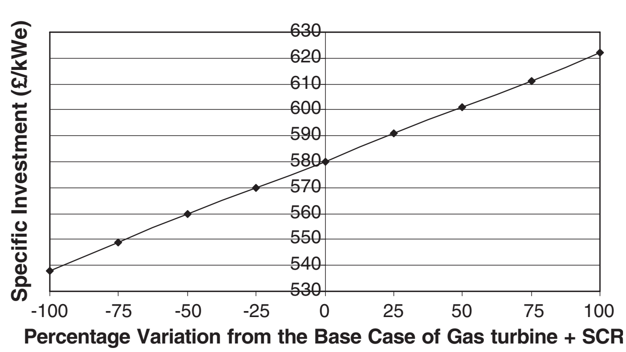

Fig. 13. Sensitivity of specific investment versus selective catalytic reduction system cost.

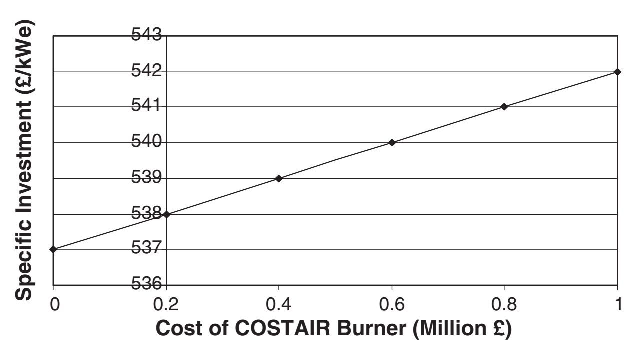

Fig. 15. Sensitivity of specific investment versus COSTAIR burner extra cost.

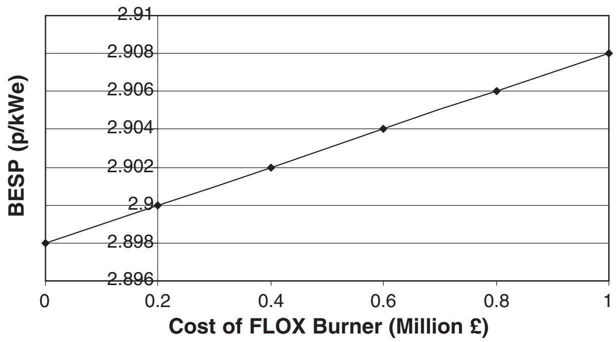

Fig. 16. Sensitivity of electricity selling price versus FLOX burner extra cost.

finally it suppresses formation of thermal NO_x. This reduces the net power production by 1.78 to 426 MWe and the lower heating valve efficiency from 33.5% to 33.2%. The main environmental change is the 80.4% reduction in NO_x emissions from 112 to 22 mg/m^3 (5% O_2).

Use of continuous staged air combustion increases the cost of electricity but to a lesser degree. With a natural gas price of £1.72/GJ (£60/per 1000 m^3), shown in Fig. 10, a break-even electricity selling price of 2.86 p/kWh is found; with a natural gas price of £2.0/GJ (£69.8/per 1000 m^3), the break-even electricity selling price is calculated at 3.12 p/kWh, which is 0.02 p/kWh above the simple gas turbine cycle, to reduce 80.4% of NO_x emissions. Similarly, where natural gas is priced at £3.0/GJ (£104.7/per 1000 m^3) the break-even electricity selling price is raised to 4.07 p/kWh, which is 0.04 p/kWh higher than that of the simple cycle gas turbine.

4.4. The results of simple cycle gas turbine with a FLOX combustor

For flameless oxidation, the main change in the technical and environmental results is to use the high internal flue gas recirculation which leads to a dilution of the combustion zone. This results in a controlled conversion of fuel without pulsation and with complete burn-out. Due to the high recirculation ratios, the maximum reaction temperature in flameless oxidation operation is much lower than in conventional combustion, thus reducing NO_x formation considerably. This reduces the net power production by 5.38 to 413 MWe and the lower heating valve efficiency from 33.5% to 32.7%. The main environmental change is the 92.3% reduction in NO_x emissions from 112 to 8.6 mg/m^3 (5% O_2).

Application of flameless oxidation increases the cost of electricity, but to a lesser degree. With a natural gas price of £1.72/GJ (£60/per 1000 m^3), shown in Fig. 11, a break-even electricity selling price of 2.90 p/kWh is found; with a natural gas price of £2.0/GJ (£69.8/per 1000 m^3), the break-even electricity selling price is calculated at 3.17 p/kWh, which is 0.07 p/kWh above the simple gas turbine cycle, to achieve 92.3% reduction of NO_x emissions. Similarly, where natural gas is priced at £3.0/GJ (£104.7/per 1000 m^3) the break-even electricity selling price is raised to 4.14 p/kWh, which is 0.11 p/kWh higher than that of the simple gas turbine cycle.

5. Sensitivity analysis of the effect on the costs of the above systems

Figs. 12–17 show the sensitivity of the effect on the costs of the above systems, i.e., Break-Even Electricity Selling Price (BESP) and the Specific Investment (SI) versus the costs of the above systems. The discussion is based on a simple cycle gas turbine system base case, costing 533 £/kWe, with a lifetime of 20 years, and natural gas priced at £1.72/GJ (£60/per 1000 m^3).

5.1. Sensitivity analysis of the effect on the cost of the SCR system

Figs. 12 and 13 show the sensitivity of BESP and SI versus the Gas turbine plus Selective Catalytic Reduction System (SCR). In the base case of Gas Turbine and the SCR base cost of 9 Million pounds, the system has the highest BESP of 3.01 p/kWe, and the highest SI cost, of 580 £/kWe. If the cost of SCR is reduced (while keeping gas turbine cost at the base case level), both BESP and SI decrease, and vice versa.

5.2. Sensitivity analysis of the effect on the extra cost of the COSTAIR combustor

Figs. 14 and 15 show the sensitivity of BESP and SI versus the COSTAIR combustor cost. In the base case of Gas Turbine and the COSTAIR combustor (burner) extra cost of 0.2 Million pounds (against the standard combustor), the system is of a BESP of 2.85 p/kWe and a SI of 538 £/kWe. If the additional cost of COSTAIR combustor be reduced (while keeping gas turbine cost at the base case level), both BESP and SI decrease, and vice versa.

5.3. Sensitivity analysis of the effect on the extra cost of the FLOX combustor

Figs. 16 and 17 show the sensitivity of BESP and SI versus the Gas turbine plus FLOX burner. In the base case of Gas Turbine and the FLOX burner extra cost of 0.2 Million £, the system has a BESP of 2.90 p/kWe and a SI of 547 £/kWe. If the additional cost of the FLOX burner was reduced (while keeping gas turbine cost at the base case level), both BESP and SI would decrease, and vice versa.

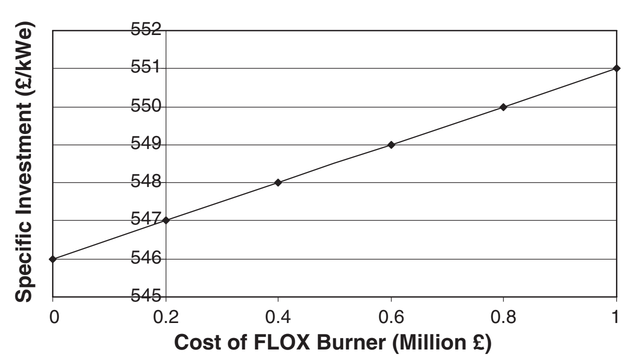

Fig. 17. Sensitivity of specific investment versus FLOX burner cost.

Table 3
A comparison of sensitivity of BESP of four NO_x reduction systems

Technology used	NO_x emissions (mg/m^3) (5% O_2)	NO_x decrease (%)	SI (£/kWe)	SI increase (%)	BESP (p/kWe) (fuel cost 1.72 £/GJ)	BESP increase (%)	BESP (p/kWe) (fuel cost 2.0 £/GJ)	BESP increase (%)	BESP (p/kWe) (fuel cost 3.0 £/GJ)	BESP increase (%)
Gas turbine only	112	–	533	–	2.83	–	3.10	–	4.03	–
SCR	11.2	90	580	8.8	3.01	6.4	3.28	5.8	4.23	5.0
COSTAIR	22	80.4	538	0.9	2.85	0.7	3.12	0.6	4.07	1.0
FLOX	8.6	92.3	547	2.6	2.90	2.5	3.17	2.3	4.14	2.7

A comparison of BESP and SI of these four NO_x reduction systems on the base case is shown in Table 3. The percentages of increase of SI (SI %) and BESP (BESP %) over the base case are also shown in the table.

6. Conclusions

The above assessment of alternative NO_x reduction technologies to the conventional simple gas turbine cycle was successfully completed using the ECLIPSE process simulator.

Compared to the conventional simple cycle gas turbine power generation, the NO_x emissions were reduced by 90% using SCR; using a COSTAIR combustor it was reduced by 80.4%; using the FLOX combustor it was reduced by 92.3%.

With a natural gas price of £1.72/GJ (£60/per 1000 m^3), £2.0/GJ (£69.8/per 1000 m^3) and £3.0/GJ (£104.7/per 1000 m^3) respectively, the BESP, for the simple cycle with no NO_x reduction system, were 2.83, 3.09, 4.03 p/kWh and SI was 533 £/kWe; compared to this base case, the BESPs for the SCR case were 3.01, 3.28, 4.23 p/kWh, the SI was 580 £/kWe, an increase of 8.8%; the BESPs for the COSTAIR case were 2.85, 3.12 and 4.07 p/kWh. The SI was 538 £/kWe, an increase of 0.9%; the BESPs for the FLOX case were 2.90, 3.17 and 4.14 p/kWh. The SI was 547 £/kWe, an increase of 2.6% over the base case. The sensitivity analyses showed that the SCR system had the highest BESP and SI; FLOX had the medium, COSTAIR had the lowest. In Table 3 it can be seen that the use of a FLOX or COSTAIR burner would have only a small increase in SI (2.6% and 0.9%) and also in BESP (2.5% and 0.7%), but provide a considerable reduction in NO_x (92.3% and 80.4% respectively).

The results from techno-economic analysis showed that the COSTAIR and FLOX cases had technical and economic advantages over SCR. This would make them attractive options for low NO_x combustors in gas turbine system in the near future.

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