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PLEASE CITE THE PUBLISHED VERSION

<http://dx.doi.org/10.1016/j.energy.2010.09.020>

PUBLISHER

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VERSION

AM (Accepted Manuscript)

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Bass, Robert J., W. Malalasekera, Peter Willmot, and Hendrik K. Versteeg. 2019. "The Impact of Variable Demand Upon the Performance of a Combined Cycle Gas Turbine (CCGT) Power Plant". figshare. <https://hdl.handle.net/2134/10692>.

The Impact of Variable Demand Upon the Performance of a CCGT Power Plant

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ABSTRACT

This paper presents experimentally measured data showing the impact of variable demand on a modern 800 MW CCGT plant. The results contrasting the performance of the plant when operating under optimum conditions with those measured when modulating the output to match dispatch instructions is presented and compared. These contrasts include the impact of step changes, continual modulation and both hot and cold starts of the plant. The results indicate the changes in fuel used per MWh, CO₂ emitted per MWh and the NO_x emissions under different operating modes. From the subsequent analysis significant increases were recorded in both fuel used and CO₂ emitted when the plant departs from optimum operating conditions. When the plant is requested to cease generating due to over capacity of the system, major increases in the emissions of NO_x, when required to restart generation together with large increases in the fuel used and CO₂ emitted per MWh, can be observed.

KEY WORDS – CCGT, Energy, Electricity Demand, Wind Energy Integration

1. INTRODUCTION

Now that there is a clear understanding of the impact of climate change due to the release of CO₂ into the atmosphere [1] from the combustion of fossil fuels, there is a worldwide drive to replace fossil fuels by sources of renewable energy. Required levels of greenhouse gas reduction have been identified through research and these requirements have been documented [2,3]. Many countries world wide have set targets to reduce green house emissions and increase efficiency of current generation systems. Compared to 1990 levels the European Union for example aim to reduce greenhouse gases emissions by 20%, increase energy efficiency by 20% and increase the amount of renewable energy use by 20% [4,5] by

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the year 2020. This is known as the 20-20-20 target to be achieved by the year 2020. The UK has set itself a more ambitious target to achieve a 60% reduction by the year 2050 [5,6,7]. Bio-fuel, onshore wind, offshore wind, tidal, wave, geothermal, hydroelectric and solar are some of the renewable or 'green' energy sources which are considered to be alternatives to fossil fuel based energy for the future [7]. European Union also aims to achieve higher renewable energy targets by the year 2050 [8]. However, many of these alternative sources are either variable and unpredictable or variable but predictable and therefore introduce increased volatility into the supply-balancing requirement.

Modern industrial countries are dependent upon a secure supply of electricity to function efficiently. Until recent times the bulk of this power has come from fossil fuel and nuclear power sources. In the light of the need to increase the proportion of renewable energy use various countries have adopted different approaches. The main factors which determine the energy policy of a country are (1) pathways to cut carbon dioxide emissions by internationally agreed amounts; (2) to maintain reliable energy supplies; (3) to maintain economic growth and to improve productivity; and (4) heating and other household energy needs are adequately maintained [7]. Add to this the way energy is used in transport infra-structures are also expected to change from direct fossil fuels to other modes of energy such as hydrogen, fuel cells and electric/hybrid. Therefore the types of energy availability to support these changes will also be a factor in determining energy policies. A number of papers in the literature have discussed different approaches adopted by different countries. Laird and Stepfles [9], for example, have discussed how Germany and United States have different policies for supporting renewable energy. The paper describes how Germany and United States have started with very similar policies for renewable energy after the energy crisis of the 1970's but by the year 2000 were on very different policy paths. Today Germany appears to be well ahead of the United States in terms of installed capacity and highly successful export markets.

UK energy policy for the present and the future is described in details in BEER 2003 [5] and BERR 2007 [10]. In the interest of security of supply and considering the need to reduce green house emission, UK has considered the possibility of increasing the nuclear power capacity in the future as part of its energy policy [10, 11]. However short term power needs require a combination of other power generation technologies. Pattersson and Soderholm [4] have discussed in detail the impact of climate policy and technology learning from future investments in the Swedish power sector. The paper suggests that renewable power will benefit from existing EU climate policy measures and overall additional policy instruments are needed to stimulate the diffusion of renewable power. Østergaard [12] using western Denmark as an example has reviewed a number of possible optimisation criteria for the design of energy systems with large share of fluctuating renewable energy sources. The analysis demonstrates that whether the system in question is modelled as operated in island mode or not has a larger impact on the definition of the optimal wind power level. The study shows that the optimisation criteria need to be clearly defined as different optimisation criteria can render different results. Mamlook et al [13] have used a neuro-fuzzy logic approach to determine the most suitable option or options for electricity production for Jordon. This approach allows to condense a large amount of data into small sets of variable rules and uses a neural network approach to reach decisions. Based on cost-to-benefit ratios, the results show that solar, wind and hydropower which are renewable energies are considered best systems for electricity power generation in Jordon. The study also shows that nuclear is the worst option followed by fossil fuel for power generation. Similar neural networks approach has been used by Ekonomou [14] to analyse Greek long-term energy consumption and such tools are very useful in determining how renewable could be integrated into long term energy policies. Chen et al [15] have discussed solutions involving fuel cells, renewable energy sources and hydrogen infrastructure for sustainable development of islands and remote regions of EU. This paper concludes that the global development of new renewable energy

technologies can assure sustainable supply of power for islands. He et al [16] have analysed the co-benefits of energy policies in China. The study shows through analysis and modelling that the policies formulated to improve energy efficiency are also effective in abating emissions resulting in substantial environmental benefits. There are many other studies dealing with various individual circumstances of each country [17-22]. The article by Jacobson and Delucchi [23] has discussed the possibility of obtaining all the world energy from wind, water and solar power. The authors argue that all what is required is sensible energy policies and large capital investment for developing required grid networks and resources. Lund [24] has also discussed in detail the perspective of renewable energy (wind, solar, wave and biomass) with respect to making strategies for sustainable development. Major technological changes identified in this analysis are energy savings on the demand side, efficiency improvements in the energy production and replacement of fossil fuels by renewables which are exactly the long term goals of the European Union energy policy. Based on the case of Denmark this paper discusses the problems and perspective of converting present energy systems to 100% renewable energy systems and concludes that such achievement is possible only with the advancement of technologies. Technology advancements will take time and need considerable resource allocations. Under present world economic climate resource allocations and development of new technologies will take considerably more time. Until a major portion of the power is produced by renewables existing and current fossil fuel based generating system will have to operate with maximum possible efficiency and modern CCGT power plants will continue to play a major role in many countries. The paper by Silveira et al [25] highlights benefits of CCGT plants in terms of pollutant emissions, ecological efficiency and costs.

Energy on demand is a requirement of any modern power supply infrastructure. As the demand for power varies over on a daily, weekly and seasonal basis [26], it is necessary to

balance the output from the supply side to match the demand instantaneously. The amount of renewable energy on national grid systems is increasing significantly, most of it supplied by wind power, although there is an expectation that both wave power and tidal power will be contributing increasing amounts in the future. Wind and wave sources of energy are unable to deliver a secure supply of energy as they are unpredictable and variable by nature. Tidal energy, although predictable delivers just two pulses of power every 24 hours, which vary in quantity as the lunar cycle changes [27].

We now have a degree of unpredictable and variable input on the supply side and a degree of variability on the demand side of the balancing equation which must be accommodated to ensure a stable electricity network. In the absence of stored energy, most of the supply modulation will be required to come from the remaining fossil-fuelled power plants, assuming that any nuclear capacity is restricted to supplying base load. To perform this balancing service CCGT power plants will have to depart from their optimum operating conditions not just to accommodate the variability of demand but the variability of input due to increasing renewable energy supply sector.

This paper reports the findings of experiments to measure the effect of variability upon a modern CCGT power plant as it is required to operate under conditions, that depart from optimum operation and analyses the consequential environmental impact. The analysis is based on the demand profile in the UK, it is, however, equally valid for any industrial nation with high electricity consumption and highly variable peak demand.

2. THE ADVANCE OF CCGT TECHNOLOGY

In the UK following the Electricity Act (1989) [28], privatising the electricity industry and the ‘Vesting’ of the generating and distribution assets into the hands of a number of publicly

quoted companies, the industry has selected gas fired technology to provide most new sources of power. Between 1991 and 2005 some 40,000 MW of new capacity has been constructed. It includes just one nuclear station (Sizewell B) and one small CHP coal fired plant (a total of 1,400MW). The bulk of the new capacity is based upon the Combined Cycle Gas Turbine (CCGT) process, which offers many benefits.

The CCGT process delivers thermal efficiencies of up to 60%, whilst the coal-fired stations deliver efficiencies between 30 to 36% and emit much higher pollution levels of CO₂, NO_x and SO_x. Gas turbine plants are quicker and cheaper to build, easier to finance and achieve high levels of availability. Further details of CCGT advantages in operational conditions are described in [25,29]

In a standard gas turbine cycle [30], the gases exit the turbine at approximately 600 °C. In the Combined Cycle Gas Turbine (CCGT) plants the energy in the exhaust gas is used to raise steam in a Heat Recovery Steam Generator (HRSG). The gas turbine cycle and steam cycle combine together to raise the overall thermal efficiency in the latest generating plants to about 58 to 60%. The latest gas turbines are designed to produce a constant output of 280MW with a gross electrical efficiency of 38%. A typical CCGT station will consist of two gas turbines and one steam turbine. To allow each gas turbine to operate independently at different output levels, each gas turbine exhausts into a separate HRSG.

As the thermal efficiency of the gas turbine is increased with a rise in the combustion temperature, there is continual competition to upgrade the hot gas path of the gas turbine. This has enabled higher and higher combustion temperatures to be achieved by using exotic materials for the combustion chambers and turbine blades. However, these blade coatings and combustion chamber materials are not suitable for some fuels and the most efficient machines are limited to firing on natural gas.

The operation of the turbines requires careful control of the rate of change of temperature throughout the hot path. A particularly important period of control occurs when the turbines are started from stationary. Internal temperatures of the steam turbines dictate the speed with which any power plant reaches its full capacity from a start. A 'Hot Start' may be achieved within 2 to 3 hours where a 'Cold Start' may take 4 to 8 hours.

The CCGT plants produce their highest thermal efficiencies when working at their maximum economic rating (MER). Any departure from this output power level causes an increase in the fuel consumed and effluent gases emitted per unit of power exported.

The swings of power delivered from both Group 1 and Group 2 renewable energy sources [31] will need to be counterbalanced by varying the output from the fossil fuel fired power stations. As wind power is the most developed source of renewable energy, easy to install and supported by public subsidies, it is likely to be the technology which will provide the major share of the required renewable energy input during the next 15 to 20 years. It will be necessary to have sufficient back-up as standby generating capacity to provide the power matching required to balance the stochastic nature of the wind power input. By 2020 the gas fired CCGT power stations are the plants most likely to be available to respond and generate the 'In Fill' power by varying their output.

3. TRANSMISSION STABILITY AND THE UK NATIONAL GRID CODE

3.1 The grid code

The System Operator (SO), a division of the National Grid Company, controls the electricity transmission network. The duties include electrical safety, quality and continuity of supply.

The SO uses the measure of frequency response to balance the continuously changing demand on the high voltage network to contain it within $\pm 1\%$ of the nominal setting of 50Hz. The

balance between the total load demand and the total generation output determines the system frequency at any specific moment.

There are statutory requirements placed upon the SO to maintain the system frequency within specific levels centred on 50Hz. In order to achieve the requirements generators and distribution companies are required to follow the NGC Grid Operating code [32]. The SO has to ensure that there is sufficient generation capacity and demand side response held in readiness to manage any credible system contingency. Sudden increases in demand cannot be met from the wind, wave and solar sources of renewable energy. Power delivered from these systems matches the instantaneous energy input and therefore cannot respond to meet the requirements of the Grid Code.

3.2 Gas Turbine plant operation

As a large percentage of the coal fired generating plants are gradually retired from the UK system, the frequency response service will be increasingly provided by the CCGT stations. This assumes that any of the remaining or new nuclear stations will have derogation from the National Grid code to relieve them from many of these duties.

The compliant generators must maintain their output power flow as the frequency falls from 50Hz to 49.5Hz without reducing the power output level. From 49.5Hz to 47Hz the code allows a linear fall in output, such that at 47Hz the power flow is not less than 95% of the capacity being delivered at 50Hz. This requirement is onerous; many of the latest gas turbines suffer dangerous rises in combustion temperature during frequency correction incidents. Some gas turbine manufacturers achieve the code requirements by spraying water into the air intakes of the turbine.

The Code also requires that a plant must operate on a continuous basis between 95% and 104% of the set frequency but may disconnect automatically from the network after 20 seconds when the frequency is between 94% and 95%. Most CCGT gas turbines plants can meet the code requirements when the ambient temperature is 0°C, but as the external air temperature rises, the compressor operating margin of the gas turbine falls and at 25°C substantial amounts of extra fuel is needed to deliver the power. The situation can be recovered by over-firing the turbine to achieve compliance with the code but this causes an increase in the combustion temperature of approximately 160°C. At these temperatures there is concern about combustion stability, compliance with the emission regulations and potential damage to the hot path components such as the turbine blade coatings and the rotor.

Each Gas turbine is equipped with a water spray to wash the compressor blades. It is this wash system, that is used during times of low frequency operation to reduce the combustion temperature during over firing.

Other important factors that result from the interaction of the CCGT plant with the demands of the SO are:

- (a) Start-up times and fuel used in the start-up and shut-down cycles;
- (b) The ramp rates during start-up and power output changes;
- (c) The part-load capability;
- (d) Pollution emitted as a result of generating at levels below the optimum output;
- (e) The impact upon plant maintenance times and costs;
- (f) The Impact upon fixed overheads;
- (g) The impact upon the return on capital investment.

The SO has three forms of generating reserve that can be purchased to meet the obligations.

- (a) Spinning reserve (part-loaded plant, which can be ordered to increase or decrease output as required).
- (b) Plant on hot standby (whilst not connected to the transmission system, it can be brought into service with a minimum of delay).
- (c) Plant on Cold standby (This plant is awaiting orders to commence the process of warming the plant prior to commencing synchronising routine).

This study has approached the issue from a different position. In order to meet the power supply and balancing requirements by 2020, it is predicted that a number of CCGT plants will be installed. The plants are inherently more efficient than Open Cycle gas Turbine (OCGT) plants as the waste heat from the gas turbines is used to add a steam cycle to the process and generate further power. (Thermal efficiencies of 58 to 60% are achieved using the combined cycle where as the open cycle can only achieve efficiencies of 36 to 38%). Both plants can deliver the necessary load following required to match the customer daily variations and the stochastic input from the increasing wind turbine capacity. However, the CCGT plants are more efficient in the use of fuel and are therefore capable of delivering lower emission levels even when they are operating on part load.

In order to examine the potential of the CCGT to fulfil the balancing duties in practice, data was collected from a new 800MW (nominal) CCGT plant over a period of 4 months. This has enabled an analysis of fuel usage and gas emission levels to be presented for hot and cold start-up, load step changes and continual modulation. The results were then compared with the results obtained when the plant was operating at or near its optimum (i.e. the plant MER). It should be noted that the data for each case considered below have been taken from a single run operating under the considered mode.

4. EXPERIMENTAL INVESTIGATIONS

The experimental data was collected from an operating CCGT plant, which has the following specifications:

Number of Gas Turbines (GT)	2
GT power rating	280MW
Steam turbine (ST)	320MW

(Figure 1)

A schematic of the CCGT plant is shown in Figure 1. The two gas turbines feed hot gas into separate heat recovery steam generators (HRSGs). The steam output is combined and then passed to a single steam turbine. The three alternators feed directly to the National Grid 400kV substation through separate step-up transformers.

All the data was collected using the official statutory metering systems. The gas input and the power output records are used to calculate the revenue flows and the NO_x measurements are those reported to the regulatory authorities. The gas flow rates were supplied from the transmitting meters sending pulses every 5 minutes. The electrical power output from each alternator was recorded individually and data collected every 5 minutes. The carbon dioxide data was taken from the calculated value reported to the statutory bodies and for carbon trading purposes. It was also recorded every 5 minutes. The oxides of nitrogen were collected from the chemi-luminescence monitoring system used for reporting purposes to the Environment Agency (recorded every 5 minutes).

5. THE TEST ROUTINE AND ANALYSIS

Plant data was examined to identify a number of different operating patterns, which were then used to analyse the impact of varying load profiles. The data groups were chosen to demonstrate the consequences of operating under various regimes such as constant load, load

balancing and starts/stops. In order to obtain reliable data a sufficiently long period was selected to ensure the conditions represented a stable period of plant operation.

The test data were collected for following operating conditions:

1. The CCGT plant operating at Maximum Economic Rating (MER). This is also known and maximum commercial rating (MCR).
2. A Cold Start.
3. A Hot Start.
4. A step change.
5. A period of modulated power output.

Each data group was analysed for the efficiency of operation, the fuel used per MWh, the CO₂ produced per MWh and the NO_x emitted mg/m³. It should be noted that the unit ‘t’ used below is for metric tonnes.

Let

G_f = Energy in gas flow (GJ)

G_t = Total gas energy consumed over test period (GJ)

P_o = Power Output (MWh)

P_t = Total Power Output (MWh)

C_e = Carbon Dioxide emitted (t) in metric tonnes

C_a = Average Carbon Dioxide emitted during test period (t/MWh)

C_t = Total carbon Dioxide emitted over period (t) in metric tonnes

T = test period (hrs)

N_o = Nitrogen oxides emitted (mg/m³)

N_t = Average NO_x emitted during test period (mg/m³)

Then Total Gas flow over test period is given by

$$G_t = \sum_{t=0}^{t=T} G_f \quad (\text{GJ}) \quad (1)$$

Total power output

$$P_t = \sum_{t=0}^{t=T} P_o \quad (\text{MWh}) \quad (2)$$

Energy used per MWh during test period,

$$P_a = G_t / P_t \quad (\text{GJ/MWh}) \quad (3)$$

The total CO₂ emitted during the period (C_t) in metric tonnes (t)

$$C_t = \sum_{t=0}^{t=T} C_e \quad (\text{t}) \quad (4)$$

and the CO₂ emitted per MWh generated (C_a)

$$C_a = C_t / P_t \quad (\text{t/MWh}) \quad (5)$$

All the following tests were carried out using data collected from an 800MW CCGT plant (hereafter known as Plant C), which is connected to the UK electricity grid system. It is supplied with natural gas from the national gas transmission system. It should be noted that each test represents a separate period of operations of Plant C. The data was extracted from the CCGT plant on occasions when the market demand and the operation of the plant was such that it met the test conditions we wished to examine namely, Hot Start, Cold Start, Constant Output (at MER), Load Step Change and two occasions when the power delivered by the plant was modulated between 100% of full load and 50% full load.

The observations were made during January 2005 and April 2005 when access to the plant was granted. As the plant was often required to change output before a stable period of operation could be said to exist, the data was selected when the plant demonstrated the characteristic being investigated e.g. Step Change. The ambient conditions during the test

were winter conditions in the UK. During the months in question the mean temperature was 5.7 °C.

6. RESULTS

6.1 Operating at Maximum Economic Rating (MER)

The first test was used to establish the optimum operating case for this power plant, (MER). A period of constant operation at full load was selected. The gas flow, electrical output from each alternator and emission levels of NO_x mg/m³, and CO₂ t/MWh were recorded.

Results shown in Figure 2 illustrate the constant nature of the power output at MER over a 2.75 hours period of production (33, 5 min. intervals). Figure 2(a) indicates the power produced from the two gas turbines (GTA and GTB) and the steam turbine (ST). The excursion in power output varied by ± 2 MW during the period. The key feature here is the constant and steady nature of the operation whilst producing power at the maximum plant capacity. Under these conditions the emissions levels are low and the burden on plant machinery is very low. This scenario represents ideal conditions for plant operation. Fig. 2(b) illustrates the gas flow and power output on an expanded scale and Fig. 2(c) shows the CO₂ emission pattern during MER operation and it can be seen that the CO₂ emission varied by ± 0.006 t/MWh during the test period. The emissions of NO_x released to atmosphere during this test is shown in Fig. 2(d), and it can be seen that during constant operations all emissions are well within acceptable limits and variations are very low representing the Maximum Economical Rating (MER) for the plant in the current state of maintenance.

For this case average gas consumption, CO₂ and NO_x emissions, based on total power produced during the test period was calculated. These results are summarised later in a separate section, in Table 1, along with the similar results from other tests. The principal

comparative parameters obtained from this test that will be used to evaluate the performance of the plant when the operation of the plant departs from the MER are:

Fuel Used per MWh	7.01 GJ/MWh
Average Power Output	783.4 MWh
CO ₂ emitted per MWh	0.35 t/MWh
NOx (Average emission)	45.4 mg/m ³
Maximum NOx	53.0 mg/m ³

(Figure 2)

6.2 Cold-Start operation

The data collected during this test illustrates the performance of a CCGT plant starting from a cold condition, requiring careful attention to the rate of temperature increase to protect the hot path components of the gas turbines and the expansion of the moving parts in the steam turbine. The data was collected over a period of 8.33 hours considerably longer than the data collection time of constant operation. This is due to long time required in the cold start. The sequence of events commenced with the initial firing of only one gas turbine (GT) followed by the start of generation from the steam turbine (ST) when the HRSG steam pressures and the turbine temperatures have achieved predetermined levels. Finally, the second GT was started and approximately 1.5 hours later the second HRSG was ready to supply steam to the common steam turbine. Figure 3 illustrates the results during the Cold start operation. The starting pattern of power build-up of the CCGT turbines from a cold start is illustrated in Figure 3(a). Figure 3(b) shows gas consumption which basically follows the total power curve. Figures 3(c) and 3(d) show the CO₂ and NOx emission patterns in the cold start operation. It can be seen that high emission levels results in during the start of the first gas turbine. The NOx emissions shown in Fig. 3(d) are of serious concern during the initial period

of the start-up when concentrations values (in this case above 200 mg / m³) reach levels that are only authorised by the Environment Agency for very short periods (10 to 15 minutes).

As in the previous case averaged data during the cold start operation can be calculated and these are summarised in Table 1. The comparative parameters obtained during this test are summarised below:

Fuel Used per MWh	8.16 GJ/MWh
Average Power Output	358.2 MWh
CO ₂ emitted per MWh	0.47 t/MWh
NO _x (average emission)	29.6 mg/ m ³
NO _x (maximum level)	207.1 mg/ m ³

(Figure 3)

6.3 Hot-Start operation

The hot start is able to reach full load output when the temperature of the turbines and HRSGs have only fallen marginally from operating conditions. This occurs after an outage of 2 to 4 hours. Typical patterns of gas demand, turbine power production and CO₂ emissions is shown in Figure 4.

Figure 4(a) shows the power pattern from GTs and the ST. Fig. 4(b) shows the gas consumption which basically flows the total power pattern. Figures 4(c) and (d) show CO₂ and NO_x emission patterns respectively during a hot start up. The NO_x emission pattern, indicate very high levels of NO_x emissions during the fast start-up routine. Averaged results from this run are summarised in Table 1. The comparative parameters obtained during this test are summarised below:

Fuel Used per MWh	9.24 GJ/MWh
Average Power Output	344.6 MW
CO ₂ emitted per MWh	0.59 t/MWh
NO _x (average emission)	158.6 mg/ m ³
NO _x (Maximum level)	>250 mg/ m ³

(Figure 4)

6.4 Step change

In this case, the impact of a step change in the power output of the plant was monitored to measure any change in environmental emission. Generated power, gas consumption and emission patterns during a load reduction of 12% are shown in Figure 5. The individual turbine output adjustments are shown in Fig. 5(a). Gas consumption and power output is shown in Figure 5(b). The CO₂ emission and the power output are illustrated in Fig. 5(c). As the firing temperatures in the gas turbines are lower during reduced power output levels below the MER condition, the NO_x level emitted in the flue gases are lower as seen in Fig. 5(d). Average NO_x in this case is 30.7mg/m³ as compared to 45.4mg/m³ while operating under full load conditions. It should be noted that here the averaged power produced is considerably lower than the rated power value. Averaged results from this run are summarised in Table 1.

The comparative parameters obtained during this test are summarised below:

Fuel Used per MWh	7.58 GJ/MWh
Average Power Output	520.5 MW
CO ₂ emitted per MWh	0.39 t/MWh
NO _x (average emission)	30.7 mg / m ³
NO _x (maximum emission)	40.7 mg/ m ³

(Figure 5)

6.5 Modulation test

A period of variable power production at Plant C responding to the grid demand variation of $\pm 26\%$ is presented in this case to demonstrate the consequences of modulating the output. This variation of power resulted in the actual operation of the plant responding to the demand and therefore the results presented here are from a period of operation where the plant was performing the role of a power balancing unit.

The modulation test lasted 5.9 hours and the power output varied by $\pm 26\%$ about the $3/4$ of the full load output level. Results are summarised in Figure 6. The generated output oscillated between 380MW and 785MW while both gas turbines shared the load equally during the test after the second turbine was brought up to load at the beginning of the test period; this is illustrated in the power patterns in Fig. 6(a). Figure 6(b) shows the gas consumption which follows the power pattern. The emission of CO₂ during this test and the power output is shown in Fig. 6(c) where it is demonstrated that the CO₂ emission levels can be seen to rise as the load on the plant falls. Even a small variation below half the station capacity (i.e. below 400MW) appear to introduce significant rises in emissions of CO₂. The NO_x emissions during the test period are shown in Fig. 6(d). The first 30 minutes of the test when the emission levels were high occurred during a period when the station was at the lower end of the output range investigated. Averaged results from this run are summarised in Table 1. The comparative parameters obtained during this test are summarised below:

Fuel Used per MWh	7.47 GJ/MWh
Average Power generated	568.4 MW
CO ₂ emitted per MWh	0.38 t/MWh
NO _x (average emission)	22.2 mg/ m ³
NO _x (maximum level)	>250 mg/ m ³

(Figure 6)

7. CONSOLIDATED RESULTS

The results presented above, were collected over different operating periods as each scenario required different time span to complete the tests. By operating the power plant at different output levels it has been possible to compare the fuel demand, the variations in emissions (CO₂ & NO_x) and hence the costs per unit of power produced. For comparison purposes, averaged power, gas consumption and emission levels were compiled. Table 1 shows averaged quantities for all the test cases considered above.

(Table 1)

Gas used is graphically compared in Figure 7. When compared with gas used under constant operation, higher quantity of gas is used during all other load following operating conditions. It can be seen that step change and modulation modes demand more gas hence the cost of operation is higher during these modes. Average CO₂ under different modes are shown in Figures 8 and 9. It is clear that the cold and hot starts produce more CO₂ and load following operations such as a step change or modulation also produce more CO₂ than constant MER operation.

(Figures 7)

The extra CO₂ emitted (t/MWh) during periods when the power plant is operating below MER is illustrated in Fig. 10. It can be seen that considerable amount of CO₂ is emitted when the plant is not operating under constant operating conditions, which in turn increase the costs of purchasing CO₂ permits. The consequences are summarised in Table 2. The cost of the CO₂ permits varies according to the supply and demand in the trading market. In order to place a realistic measure on this cost, a nominal figure of £20/tonne has been used to compute the impact of CO₂ emissions on the plant operations, (note: £20/tonne is the predicted charge under the second phase of the CO₂ trading regime). These estimates are summarised in Table 2. Figure 10 also shows CO₂ emissions during start-ups in comparison to constant operation. During the starting periods the emission of CO₂ (t/MWh) increases significantly.

From Fig. 10 it can be seen that between 0.12 tonnes /MWh during a cold start and up to 0.24 t/MWh are emitted above the MER operating levels.

(Figure 8,9,10)

(Table 2)

When these emissions are converted into the purchasing of carbon certificates, the impact of operating the plant below MER continuously adds significant costs to the operation. It is clear from the results that more emissions results in start up periods and step changes and modulation period of operations which are required to respond to demand also produce more CO₂ than the constant operation. This is usually the case and sometimes plants will have to operate during day time only and undergo number of hot start-ups and at least one cold start up during a week. The consequence is to generate far more CO₂ as it is clear that if CCGT plants could be operated continuously at MER, level emissions are lower than load following operations responding to grid demand. Further, variable operation reduces the life span of the plant and adds to the maintenance cost. The analysis presented here can be extended to calculate predicted cost in each operation and a further study has recently been completed which attempts to examine the financial impact on a CCGT power plant of operating below optimum performance. It considers the consequences of increased fuel usage and CO₂ emissions, increases in fixed and variable overhead costs operating and maintenance costs and impact on raising capital funds for future power stations construction.

8. CONCLUSIONS

The electricity supply industry has always required reserve generating capacity in order to balance variable consumer demand and this capacity has commanded higher unit prices to compensate for the variable nature of that demand and for the extra costs incurred. The growing capacity of renewable energy sources (i.e. wind power in particular) on the supply side has introduced a new source of insecurity and variability on the system which must be

balanced. Apart from a small amount of pumped storage, it will be fossil-fuelled power stations that provides this back-up capacity and balancing service to the transmission system.

In an attempt to quantify the impact of variable demand on a modern CCGT plant, a series of tests were carried out to examine the consequences. It was found that there are a number of significant issues which must be considered as the plant departs from optimum performance, namely

- extra fuel is used per MWh exported.
- higher levels CO₂ are emitted per MWh exported.
- higher rates of NO_x emissions occur when the plant is required to stop and restart.
- as a consequence higher, maintenance, operational and capital, costs per unit of power generation is incurred.

There would be instances where renewable sources can be very variable. Particularly there could be instances where wind generation could be zero or very small. In these occasions CCGT plants which can provide supply at a short notice will have to operate at a short notice. In these situations the necessity to vary the output of the CCGT plant can be attributed to the variability of the renewable energy source (e.g. wind power). However, the extra environmental impact and the extra costs involved in generating balancing power should be directly attributable to the source of renewable power causing the imbalance. There needs to be true understanding of the net contribution of CO₂ reduction contributed by each class of renewable energy and the true cost of delivering renewable energy to the consumer.

The results show that more emissions is produced in start up periods and step changes and modulation period of operations which are required to respond to demand also produce more CO₂ than the constant operation. The consequence is to generate far more CO₂. It is clear that if CCGT plants could be operated continuously at MER level, emissions are lower than load following operations responding to grid demand. To minimise CO₂ emissions, resulting from

load balancing, some form of power storage capacity will be needed as more unpredictable and unreliable renewable energy sources are introduced.

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Figure 1. A schematic of the CCGT plant.

(a) Breakdown of power output (constant operation)

(b) Gas flow and power output

(c) CO₂ produced and power output

(d) Constant operation NO_x emission rate mg/m³ and power output

Figure 2. Measured output during constant operation of the CCGT plant
(Note to copy editor: Individual figures are available if needed)

(a) Breakdown of power output (Cold start)

(b) Gas flow and power output – cold start

(c) CO₂ produced and power output – cold start

(d) Cold start NO_x emission rate mg/m³ and power output

Figure 3. Measured output during cold start of the CCGT plant
(Note to copy editor: Individual figures are available if needed)

(a) Breakdown of power output (Hot start)

(b) Gas flow and power output – hot start

(c) CO₂ produced and power output – hot start

(d) Hot start NO_x emission rate mg/m³ and power output

Figure 4. Measured output during hot start of the CCGT plant
(Note to copy editor: Individual figures are available if needed)

(a) Breakdown of power output (Step Change)

(b) Gas flow and power output

(c) CO₂ produced and power output

(d) NO_x emission rate mg/m³ and power output

Figure 5. Measured output during step change of the CCGT plant
(Note to copy editor: Individual figures are available if needed)

(a) Breakdown of power output (Modulation)

(b) Gas flow and power output

(c) CO₂ produced and power output

(d) NO_x emission rate mg/m³ and power output

Figure 6. Measured output during Modulation of the CCGT plant.
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Figure 7. Gas used GJ/MWh for various operating conditions

Figure 8 Average CO₂ under different operating modes compared to constant operation

Figure 9 Average CO₂ during start-up modes compared to constant operation

Figure 10. Extra CO₂ emitted compared to constant operation

Table 1. Results from all tests

	Mode of operation				
	Constant operation	Cold-start	Hot-start	Step change	Modulation
Duration (hrs)	2.75	8.33	3.92	3.75	5.83
Maximum power (MW)	785.8	785.1	789.5	729.8	778.8
Minimum power (MW)	781.9	n/a	n/a	517.9	379.6
Total power (MWh)	2154.3	2984.7	1349.7	1951.8	3453.2
Average power (MWh)	783.4	358.2	344.6	520.5	568.4
Average CO ₂ (t/MWh)	0.35	0.47	0.59	0.39	0.38
Average NO _x (mg/m ³)	45.4	29.6	158.6	30.7	22.2
Maximum NO _x (mg/m ³)	53.0	207.1	1587	40.7	250.1
Total fuel used (GJ)	15107.5	24364.0	12468.1	14805.2	25716.4
Fuel used per MWh (GJ/MWh)	7.01	8.16	9.24	7.58	7.47

Table 2. Carbon Dioxide Emissions and Carbon Certificate Costs

	CO2 emissions			
	Duration (h)	CO2 Emissions (t/MWh)	CO2 excess above MER (t/MWh)	Cost of Carbon Certificates @£20/t (£)
Constant operation	2.75	0.35	-	7.1
Cold start	8.33	0.47	0.12	9.4
Hot start	3.92	0.59	0.24	11.8
Step change	3.75	0.39	0.04	7.8
Modulation	6.50	0.38	0.03	7.6