Impact of variable demand upon the performance of a CCGT power plant

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

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Loughborough, Leics, LE11 3TU, United Kingdom

ABSTRACT

This paper presents experimentally measured data showing the impact of variable demand on a modern 800 MW CCGT plant. The results of 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, CO$_2$ emitted per MWh and the NOx emissions under different operating modes. From the subsequent analysis significant increases were recorded in both fuel used and CO$_2$ 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 NOx, when required to restart generation together with large increases in the fuel used and CO$_2$ emitted per MWh, can be observed.

INTRODUCTION

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. As the demand for power varies over on a daily, weekly and seasonal basis [1], it is necessary to balance the output from the supply side to match the demand instantaneously.

Now that there is a clear understanding of the impact of climate change due to the release of CO$_2$ into the atmosphere from the combustion of fossil fuels, there is a worldwide drive to replace fossil fuels by sources of renewable energy. 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.

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 [2].

We now have 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.

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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.

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.

THE ADVANCE OF CCGT TECHNOLOGY

In the UK following the Electricity Act (1989) [3], 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, NOx and SOx. Gas turbine plants are quicker and cheaper to build, easier to finance and achieve high levels of availability.

In a standard gas turbine cycle [4], the gases exit the turbine at approximately 600 ºC. 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 [5] 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.

TRANSMISSION STABILITY AND THE UK NATIONAL GRID CODE

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 ±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 [6]. 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.

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 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).

EXPERIMENTAL INVESTIGATIONS

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

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Gas Turbines (GT)</td>
<td>2</td>
</tr>
<tr>
<td>GT power rating</td>
<td>280MW</td>
</tr>
<tr>
<td>Steam turbine (ST)</td>
<td>320MW</td>
</tr>
</tbody>
</table>
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 NOx 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).

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 NOx emitted mg/m³. It should be noted that the unit ‘t’ used below is for metric tonnes.

Let

\[ G_f = \text{Energy in gas flow (GJ)} \]
\[ G_t = \text{Total gas energy consumed over test period (GJ)} \]
\[ P_o = \text{Power Output (MWh)} \]
\[ P_t = \text{Total Power Output (MWh)} \]
\[ C_e = \text{Carbon Dioxide emitted (t) in metric tonnes} \]
\[ C_a = \text{Average Carbon Dioxide emitted during test period (t/MWh)} \]
\[ C_t = \text{Total carbon Dioxide emitted over period (t) in metric tonnes} \]
\[ T = \text{test period (hrs)} \]
\[ N_o = \text{Nitrogen oxides emitted (mg/m}^3\text{)} \]
\[ N_t = \text{Average NOx emitted during test period (mg/m}^3\text{)} \]

Then Total Gas flow over test period is given by

\[ G_t = \sum_{t=0}^{T} G_f \quad \text{(GJ)} \] (1)
Total power output

\[ P_t = \sum_{t=0}^{T} P_o \text{ (MWh)} \]  

(2)

Energy used per MWh during test period,

\[ P_u = G_i / P_i \text{ (GJ/MWh)} \]  

(3)

The total CO\(_2\) emitted during the period \((C_t)\) in metric tonnes \((t)\)

\[ C_t = \sum_{t=0}^{T} C_o \text{ (t)} \]  

(4)

and the CO\(_2\) emitted per MWh generated \((C_a)\)

\[ C_a = C_t / P_t \text{ (t/MWh)} \]  

(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.

**RESULTS**

**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/m\(^3\) and CO\(_2\) t/MWh were recorded.

Results shown in Figure 1 illustrates the constant nature of the power output at MER over a 2.75 hours period of production (33, 5 min. intervals). Figure 1(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 ± 2MW 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. 1(b) illustrates the gas flow and power output on an expanded scale and Fig. 1(c) shows the CO\(_2\) emission pattern during MER operation and it can be seen that the CO\(_2\) emission varied by +/- by 0.006 t/MWh during the test period. The emissions of NO\(_x\) released to atmosphere during this test is shown in Fig. 1(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, CO\(_2\) 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
- NO\(_x\) (Average emission): 45.4 mg/m\(^3\)
- Maximum NO\(_x\): 53.0 mg/m\(^3\)
**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 2 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 Fig. 2(a). Figure 2(b) shows gas consumption which basically follows the total power curve. Figures 2(c) and 2(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.2(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 Table1. The comparative parameters obtained during this test are summarised below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Used per MWh</td>
<td>8.16 GJ/MWh</td>
</tr>
<tr>
<td>Average Power Output</td>
<td>358.2 MWh</td>
</tr>
<tr>
<td>CO₂ emitted per MWh</td>
<td>0.47 t/MWh</td>
</tr>
<tr>
<td>NOx (average emission)</td>
<td>29.6 mg/ m³</td>
</tr>
<tr>
<td>NOx (maximum level)</td>
<td>207.1 mg/ m³</td>
</tr>
</tbody>
</table>

Figure 1. Measured output during constant operation of the CCGT plant
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 CO$_2$ emissions is shown in Figure 3.

Figure 2. Measured output during cold start of the CCGT plant

Figure 3. Measured output during hot start of the CCGT plant
Figure 3(a) shows the power pattern from GTs and the ST. Fig. 3(b) shows the gas consumption which basically flows the total power pattern. Figures 3(c) and (d) show CO\textsubscript{2} and NO\textsubscript{x} emission patterns respectively during a hot start up. The NO\textsubscript{x} emission pattern, indicate very high levels of NO\textsubscript{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\textsubscript{2} emitted per MWh: 0.59 t/MWh
- NO\textsubscript{x} (average emission): 158.6 mg/ m\textsuperscript{3}
- NO\textsubscript{x} (Maximum level): >250 mg/ m\textsuperscript{3}

**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 4. The individual turbine output adjustments are shown in Fig. 4(a). Gas consumption and power output is shown in Figure 4(b). The CO\textsubscript{2} emission and the power output are illustrated in Fig 4(c). As the firing temperatures in the gas turbines are lower during reduced power output levels below the MER condition, the NO\textsubscript{x} level emitted in the flue gases are lower as seen in Fig.4(d). Average NO\textsubscript{x} in this case is 30.7mg/m\textsuperscript{3} as compared to 45.4mg/m\textsuperscript{3} while operating under full load conditions. It should be noted that here the averaged power produced is considerable 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\textsubscript{2} emitted per MWh: 0.39 t/MWh
- NO\textsubscript{x} (average emission): 30.7 mg/ m\textsuperscript{3}
- NO\textsubscript{x} (maximum emission): 40.7 mg/ m\textsuperscript{3}

**Modulation test**

A period of variable power production at Plant C responding to the grid demand variation of ±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 ± 26% about the ¾ of full load output level. Results are summarised in Figure 5. 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. 5(a). Figure 5(b) shows the gas consumption which follows the power pattern. The emission of CO\textsubscript{2} during this test and the power output is shown in Fig. 5(c) where it is demonstrated that the CO\textsubscript{2} 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 CO\textsubscript{2}. The NO\textsubscript{x} emissions during the test period are shown in Fig. 5(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
<table>
<thead>
<tr>
<th>CO₂ emitted per MWh</th>
<th>0.38 t/MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx (average emission)</td>
<td>22.2 mg/ m³</td>
</tr>
<tr>
<td>NOx (maximum level)</td>
<td>&gt;250 mg/ m³</td>
</tr>
</tbody>
</table>

(a) Breakdown of power output (Step Change)

(b) Gas flow and power output

(c) CO₂ produced and power output

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

Figure 4. Measured output during step change of the CCGT plant

(a) Breakdown of power output (Modulation)

(b) Gas flow and power output

(c) CO₂ produced and power output

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

Figure 5. Measured output during Modulation of the CCGT plant.
CONSOLIDATED RESULTS

The presented above, was 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 (CO\textsubscript{2} & NO\textsubscript{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. Results from all tests

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

Gas used is graphically compared in Figure 6 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 CO\textsubscript{2} under different modes are shown in Figures 7 and 8. It is clear that the cold and hot starts produce more CO\textsubscript{2} and load following operations such as a step change or modulation also produce more CO\textsubscript{2} than constant MER operation.

Figure 6  Gas used GJ/MWh for various operating conditions

The extra CO\textsubscript{2} emitted (t/MWh) during periods when the power plant is operating below MER is illustrated in Fig 9. It can be seen that considerable amount of CO\textsubscript{2} 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 9 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.9 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.

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

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.

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 NOx 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.

Where 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) 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. 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.

REFERENCES