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A Rough Examination of the value of gas storage

Monica Giulietti, Luigi Grossi, and Michael Waterson,

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A Rough Examination of the value of gas storage*

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Abstract

This paper studies the impact of a fire in 2006 which removed the possibility of access to the Rough gas storage facilities covering over 80% of total UK storage, at a time when major withdrawals from storage would have likely taken place. Implicitly, it shows the value of such gas storage facilities, in a country with relatively little storage, where we might therefore see a considerable impact. We find that the major effect on activity was through an increased sensitivity of supply to prices and an increased variance in this sensitivity, not through physical shortages of gas.

*We would like to thank Platts for providing the gas pricing data used in this study and Stuart Hodges for helpful discussions. Luigi Grossi's work on the project was partially supported by MIUR grant, PRIN08 and this work grows out of the ESRC grant (RES 000221686) to Giulietti and Waterson.

1 Introduction

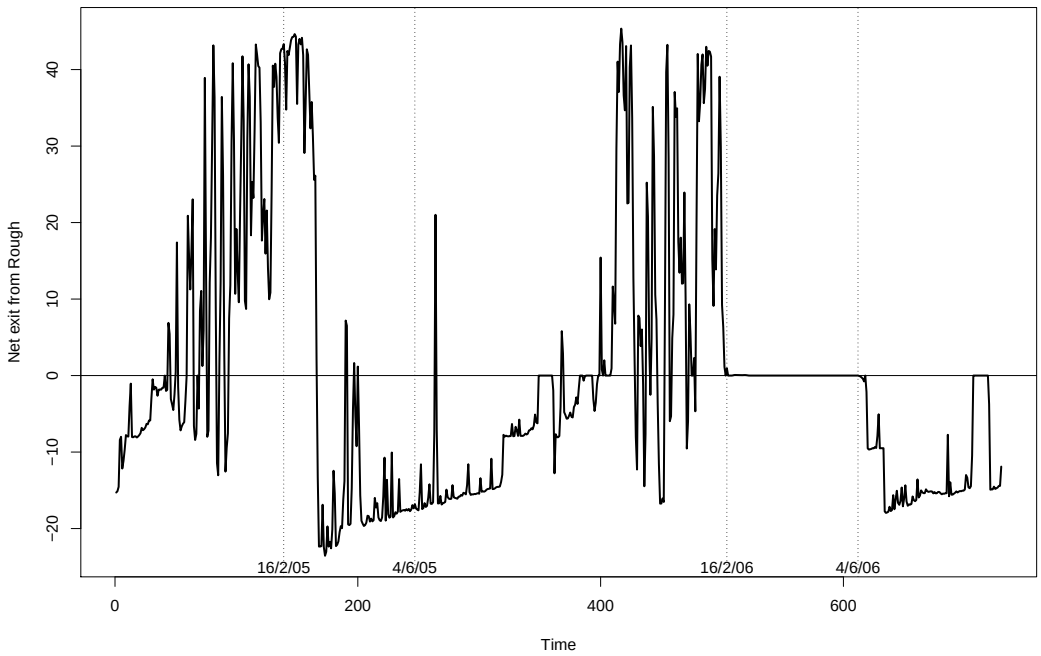
On the morning of 16th February 2006, a significant fire started on the Rough gas storage facility in the North Sea off the Yorkshire coast. As a result (in addition to two people being injured and a number having to be evacuated), the facility was shut down. Rough is the largest gas storage facility available in the UK by a considerable margin: 81% of UK storage space, 60% of daily deliverability and 42% of daily injectability (Creti and Villeneuve, 2009)[1]. The incident resulted in it being completely out of action until 11th June and partially out of action until late 2006, with "Force Majeure" being completely lifted on 20th November 2006. So in one day, in winter, and without warning a major source of supply flexibility was taken out of the system. Figure 1 illustrates Rough usage by comparison with the previous year- note the heavy withdrawals there. Our aim is to study the impact of this, totally unexpected, incident on the gas market in terms of supply and prompt gas prices. In short, we consider the revealed value of storage.

There are important contexts to this analysis. Many powerful industry figures claim that the UK is in some sense short of storage facilities for natural gas. As a representative, for example: "The UK has much lower levels of gas storage capacity than other European gas consuming countries. The Chemical Industries Association told us that whereas the UK has 13 days of storage, Germany has 99 days and France has 122 days." (House of Commons Business and Enterprise Committe (2008), at paragraph 27). It is clear more broadly that the UK has far less storage, when measured against international benchmarks (see table 1), than other European countries.[2] Thus it might be argued that if, for example, Germany has the "correct" level, the UK is woefully short, so a major reduction would have been critical; if the UK level is or was appropriate, Germany has taken out a very expensive insurance policy.

[1] Others give slightly different percentages but the message is the same: this facility dominates the market for storage.

[2] It is true that more storage is currently in development in the UK, potentially doubling UK storage capacity. However this would leave the UK far short of the German or French figures.

Figure 1: Net withdrawals from storage: 2005-06 and 2006-07



Source: National Grid 2006

Table 1: Natural Gas Storage, end 2009. Selected countries

Country	Annual consumption (mcm)	Working capacity (mcm)	Peak output (mcm/day)	Implied average days supply	Max extraction rate
Austria	8802	4639	54.8	192	2.27
Belgium	17188	709	24.0	15	0.51
France	44507	12395	248.4	102	2.04
Germany	92646	19866	465.1	78	1.83
Italy	78051	14295	271.1	67	1.27
Netherlands	48796	5078	177.0	38	1.32
Spain	33884	2726	14.5	29	0.16
UK	90759	4310	113.0	17	0.45

Source: IEA Statistics: Natural Gas Information 2010

There is an additional policy context- Rough is owned by Centrica, a powerful player in the retail gas market. The question of whether Centrica's ownership continues to give it market power sufficient to imply the need for constraints on Rough's operation is considered by the UK Competition Commission (2011) (and Competition Commission,

2003).[3]

Finally, there are analytical contexts. This paper is one of a small number of papers in economics examining the impact of major events on the economy. A key paper here is Bloom (2009) who has a Macro context to his globally significant events like the 9/11 terrorist attacks. We have the advantage of a very specific limited event enabling a comparatively clean experiment. By contrast, existing analytical methods of valuing gas storage use a range of more or less complex techniques involving options valuation and simulation (see e.g. Bringedal, 2003; Hodges, 2004; Byers, 2006; Li, 2007).

The difficulty in evaluating an idiosyncratic insurance policy lies in knowing what would happen in its absence.[4] What is the nature of the peril that is being insured against? The Rough fire provides what is probably a unique insight into the value of storage (within the context of a market-oriented energy system), given its sudden absence and its significant size in relation to the whole. Since gas supplies were maintained without interruption (and we later conclude that demand was not constrained during the cold spell in March following the fire, when supplies could not be called forth from Rough storage), the impact can be measured through the impact on price. We naturally expect that, when normally available in winter months, Rough is used when it is cheaper to call supplies from there than to arrange them from another source, for example LNG. Thus, one price impact we may expect is on mean price. Bloom (2009) reminds us that we may also expect an impact on uncertainty, or the variance in price. We investigate both these potential effects.

In the following sections, we first discuss the significance of storage in the gas market

[3]Michael Waterson is a member of the UK Competition Commission (hereafter CC) but has no access to its work on topics different from any member of the general public. He writes here in an entirely personal capacity.

[4]Evaluating a common insurance policy is much more straightforward. If I fail to insure my house against theft of the contents, I have quite a clear general idea of the potential impact of a burglary occurring.

generally and relate this to the specific role of Rough. This leads us in the following section to modelling the likely impact on market behaviour in the aftermath of the fire. We then move to estimating the impact of the fire on demand and price movements. Here it is vital to recognise that temperature has a large impact on gas demand in the UK, with colder days requiring more gas, therefore a greater likelihood that Rough, if available, will be drawn upon and, if unavailable, will imply drawing from more expensive sources, or running short. We establish a demand relationship with temperature, then a relationship between the level of demand and supply price. In order to check that we are capturing effects of the Rough fire, not some other event, we engage in a sensitivity analysis in the penultimate section, following which we have a few concluding remarks. A short appendix (Appendix 1) contains what is very much a back-of-the-envelope evaluation of the costs of storage, to put against the revealed benefit, whilst Appendix 2 summarizes the chronology of the key events from the perspective of the Centrica website.

1.1 Some relevant literature

The impact of uncertainty on commodity markets and optimal storage policies have been investigated in the economic literature from the early 1980s. Two seminal papers in this context are Teiseberg (1981) and Wright and Williams (1982) which investigate the strategic role of storage in the US oil industry in the presence of uncertainty due to potential import disruptions. These contributions use a simulation approach in order to identify optimal storage policies for producer and consumer countries in response to potential disruptions in international oil markets of a similar nature to the two OPEC crises in the 1970s. The theoretical framework of Teiseberg (1981) and Wright and Williams (1982) has been used by Hallet (1984) to identify optimal stockpiling rules for the copper market, while Deaton and Laroque (1992) adopt a competitive storage model similar to Wright and Williams (1982) to explain the behaviour of prices for 13 agricultural and metal commodities.

More recently the European gas market has been subject to disruptions following the Russia-Ukraine dispute which interrupted the flow of gas to European countries.

This incident motivates Morbee and Proof (2010) to investigate the impact of Russian unreliability on the European gas market. Interestingly, they come to the conclusion that for most countries buying from sources other than Russia at a premium is preferred to building storage capacity. More recent contributions about the role of storage in the natural gas market include Linn and Zhu (2004) and Mu (2007). Both studies investigate price determinants in the US natural gas market and find that changes in storage levels or news about storage levels affect both the level and the volatility of gas prices.

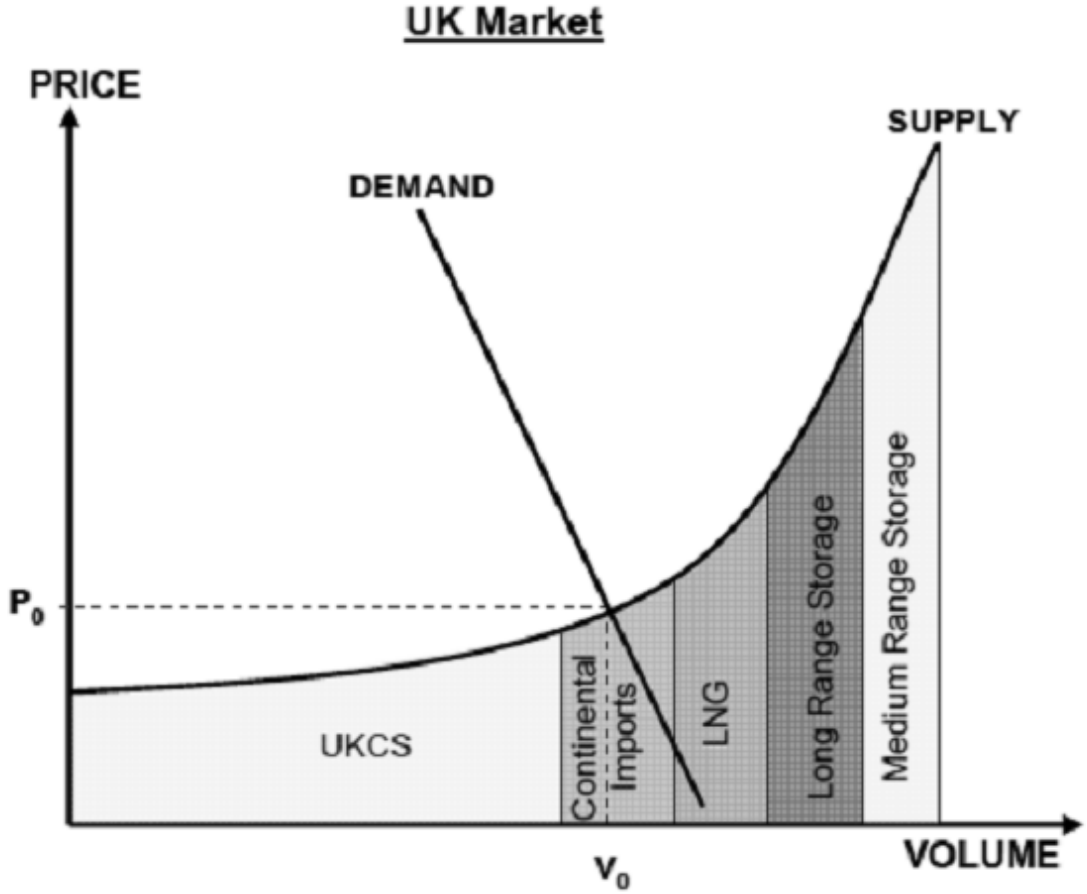
An investigation of optimal levels of storage capacity in the context of the UK economy is provided in Creti and Villeneuve (2009), whose interest in the UK case is due to the fact that it has relatively low levels of storage capacity compared to other large European countries such as France and Germany. Although their model is calibrated to UK data they do not investigate the effect of an exogenous shock to the market, such as the Rough fire, rather they model the probability of moving permanently from a state of "abundance" to a state of "crisis" according to an exponential function with publicly known parameters. Their simulation analysis leads them to conclude that the decision not to build strategic gas stocks could be an inefficient policy for the UK, in the presence of possible interruptions to one or more supply sources or fluctuations in demand. Bjerksund *et al.* (2011) also use a simulation approach to assess the value of UK storage assets. They extend the spot price model traditionally used to estimate storage value (e.g. see Hodges, 2004) by simulating a forward price curve based on the UK spot and forward prices. They find that the inclusion of complex forward dynamics in the model allows them to capture the actual storage flexibility value better than traditional models.

1.2 The market for gas storage

Figure 2 below shows schematically how gas storage fits in to the overall pattern of gas demand and supply in the UK, a (declining) producer of natural gas.

Gas storage potentially provides both security of supply and flexibility of supply. At lower levels of demand, storage is not called upon for supply, in fact at low levels of

Figure 2: Theoretical example of UK demand and supply



Source: BERR 2007

demand (and associated low prices), gas will be injected into storage, to be called upon when demand is higher. The Rough facility slots in as a supply mechanism at higher levels of demand. In its absence, given the limited significance of medium range storage, alternative sources such as imports from Norwegian gas fields, the Continent and outside the Continent must be attracted away from other destinations by higher prices.

One change since the figure below was drawn (so post-fire) is that new LNG receiving facilities in the UK has been built, so LNG imports have grown significantly in importance. (Such imports only re-commenced in a significant way in 2005). These may either be less or more expensive than gas from storage, so that LNG has become one of the main alternatives to drawing from storage. Competition for cargoes is worldwide, with Japan being the largest importer and Spain being the most significant within Europe (Competition Commission, 2011).

There are two views on gas storage policy in the UK. On one view, the UK requires much less gas storage than other European countries of a similar size, because unlike them it is a producer of natural gas and so has secure supplies and can benefit from "swing" allowing it to flex supply facilities in response to demand. The strength of this view is diminished as the UK increasingly becomes less of a producer of gas and more an importer. Deloitte (2010) provides a balanced assessment of this changing position. The second view, from more of an engineering perspective (e.g. Major, 2011) is that the UK is very short of storage and talks of "increasing fears for Britain's vulnerability". A plausible response to that view is that the UK relies on market mechanisms, and if demand is such that prices rise significantly, more gas will be forthcoming from third countries that are gas producers and wish to seek the highest price for their gas. In other words, flexibility of supply in response to price obviates the argument regarding security of supply. An examination of the Rough episode can cast light on this debate.

A further point to note here is that the "shortage of storage" school points to higher prices for customers as a result of the policy adopted. However, storage is by no means free and constructing more storage means that users will ultimately need to pay for it, presumably in terms of higher prices, albeit dispersed more around the year. Table 2 shows the dominant position of Rough in 2003 and the recent CC report comes to a provisional view that Rough remains dominant in the UK market for storage.[5]

2 Modelling the impact of the Rough fire

It follows from the discussion above that at lower levels of demand, we should not expect Rough being called to supply gas from storage. Therefore if, following the fire, demand was low (for example, if the fire had taken place in April rather than February) we would

[5]The Competition Commission (2011) did investigate the period of Rough part of the analysis. Crucially, however, they did not relate any movements to temperatures experience, simply looking at the pattern of prices and flows.

Table 2: Flexible gas capacity

	2002/03		**2009/10**	
	Max flexibility	% total	Max flexibility	% total
Market	GWh		GWh	
Storage	39,245	15.7	45,332	11
Rough	30,344	12.1	34,265	8.6
MRS	5,055	2.0	9,804	2.4
LNG	3,846	1.5	1,263	0.3
Supply	166,399	66.6	338,533	85
Beach	117,645	47.1	151,266	37.8
UKCS			76,568	19.1
NCS			74,698	18.7
Continent and LNG imports	48,754	19.5	187,267	46.8
IUK		19.5	51,000	12.7
BBL			44,371	11.1
LNG			91,896	23
Demand	44,305	17.7	16,165	4.0
Interruption	44,305	17.7	16,165	4.0
Power switch to oil			0	0
Total market	249,948	100	400,030	100
Centrica total flexibility	115,827	46.3	72,738	18.2

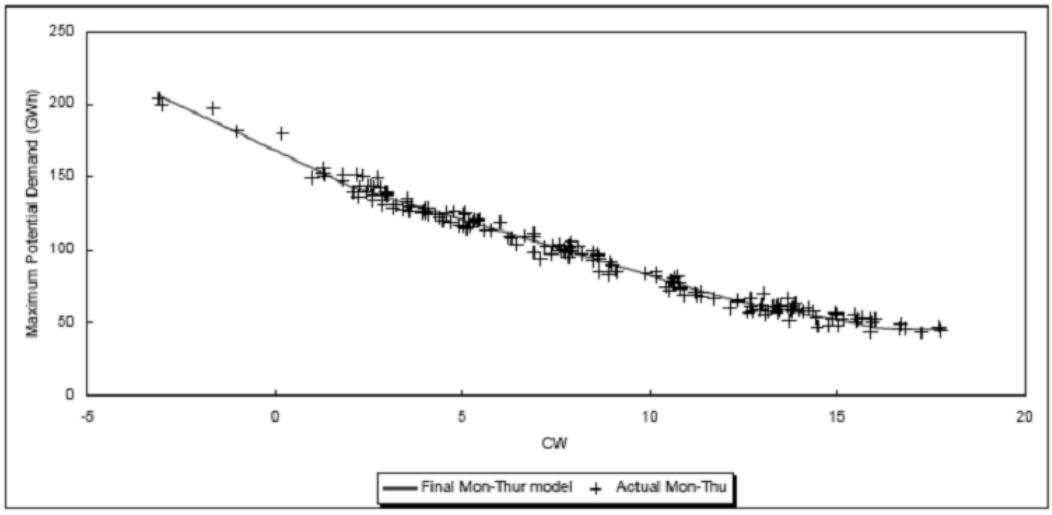
Source: Competition Commission 2011

not expect it to have any immediate impact on the market. More specifically, it would only be expected to have an impact on days when demand was high enough to mean alternatives to Rough need to be attracted to the UK from other markets. In fact shortly after the fire, around 28 February 2006, temperatures did fall well below normal and (somewhat more unusually) remained there into late March almost without respite for over three weeks, with the mean day's temperature several times being below 0°C.

The National Grid argues cogently that in the short run, demand for gas is insensitive to price, but is very sensitive to temperature. Figure 3 below, extracted from National Grid (2007) illustrates the extremely close relationship they observe between demand and a "composite weather" variable which incorporates temperature (current and one day lagged), a pseudo seasonal normal effective temperature that displays a sine wave pattern with annual periodicity, and wind chill. This graph is subsequently smoothed by them to a linear relationship incorporating "cold weather upturn" and "summer cut-off",

but we can think of it as a series of linear sections relating to temperature, wind-chill and deterministic periodicity.[6]

Figure 3: Monday to Thursday demand and composite weather



Source: National Grid 2007

On the other hand, it is clear from figure 2 and our description above that supply is significantly sensitive to price in the short (and long) run. Moreover, gas demand and supply need to be approximately in balance on every day[7]. Thus conceptually, our framework for the gas market is as follows:

[6] Of course in the longer term, decisions can be made about choice of fuel stock for industrial processes, electricity generation etc, but in the short run, particularly when it is cold, there is relatively little scope for varying the generation mix beyond the normal variations that would be practised anyway whether Rough was in operation or not. CCGT power plants with distillate backup (that can therefore switch) have a total gas use in normal operation of around 12mcm/day, that is around 2.5% of maximum daily gas demand (International Energy Agency, 2007).

[7] Unlike electricity, there is some flexibility afforded by the degree of "line packing" or pressure in the delivery system, so that demand and supply need not literally balance, but clearly this has very short run impact

$$
\begin{aligned}
D_t &= D(T_t); D' < 0 && (1)\\
S_t &= S(P_t); S' > 0 && (2)\\
D_t &= S_t \text{ in equilibrium} && (3)\\
\text{Hence} &: \\
P_t &= S^{-1}(S_t) = S^{-1}[D(T_t)] && (4)
\end{aligned}
$$

where D is demand, S is supply, T temperature, t time and P price.

Once the Rough fire rendered that storage facility non-operational, the model must take account of its impact, suggesting an alternative supply relationship (subscript F for fire):

$$
\begin{aligned}
S_t &= S_F(P_t); S' > 0 && (5)\\
D_t &= S_t \text{ in equilibrium} && (6)\\
P_t &= S_F^{-1}(S_t) = S_F^{-1}[D(T_t)] && (7)
\end{aligned}
$$

However, this will only arise once demand exceeds a certain level. Treating this level as deterministic, the model becomes (1) plus:

$$
\begin{aligned}
S_F(\cdot) &= S(\cdot); S_t < \bar{S} && (8)\\
\text{So } P_t &= S_F^{-1}[D(T_t)]; S_t \geq \bar{S} && (9)\\
P_t &= S^{-1}[D(T_t)]; S_t < \bar{S} && (10)
\end{aligned}
$$

where $\bar{S}$ is to be determined. To put it another way, our model assumes that the demand relationship is unaffected by the Rough fire, but the supply side is. Clearly we

need to test these assumptions empirically.

An alternative framework on the supply side would be to introduce some uncertainty into the process. Then, rather than storage being either drawn upon or not depending on the level of supply compared with $\bar{S}$, there might be an increasing probability that storage might be drawn upon. So let $\rho_t = \rho(S_t), \rho' > 0$ be the probability that Rough storage would have been drawn upon as a part of the supply. Then in terms of the previous model,

$$P_t = S_F^{-1}[D(T_t)]; \rho_t = 1 \tag{11}$$

$$P_t = S^{-1}[D(T_t)]; \rho_t = 0 \tag{12}$$

Therefore, as ρ increases , due to a fall in temperature, there is an increasing chance that we switch from the second region in the above expression to the first. This will introduce some variance into the process.

In the next section, after describing the data sources, we turn to analysis. We first show the broad effects of the fire, then turn to establishing equation (1) and finally, towards the end, examine the system represented by equations (8) to (10). The alternative framework (11) and (12) is investigated in Section 4.

3 Data sources, preliminary analysis and hypothesis testing

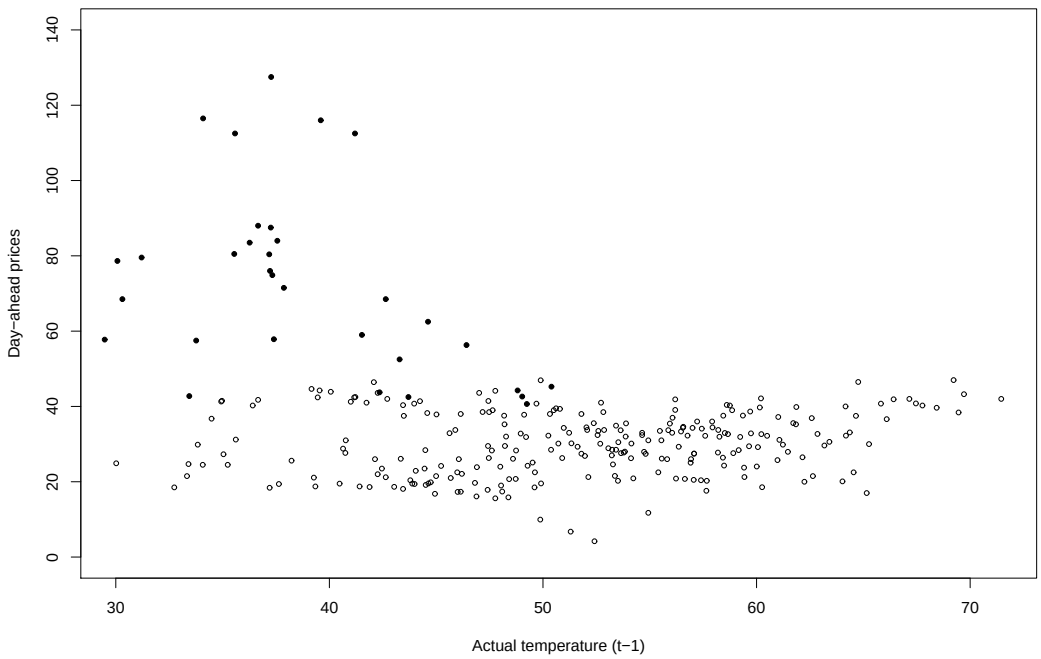
The empirical analysis has been carried out using data on day-ahead gas prices, gas demand and temperature in UK. Gas prices, labelled UK-NBP, which have been provided by Platts, are 5-days a week data and are measured in p/th. For each day the maximum and minimum prices are available, thus single daily data has been computed averaging the two values. Actual demand and temperature data are collected seven days a week

and have been downloaded from the National Grid website. Both actual demand and historical national seasonal normal demand data were obtained. Demand is measured in MWh whilst temperature is measured in degrees Celsius. In order to avoid computational problems with negative data, particularly when log-transformation is needed, we decided to convert temperatures to degrees Fahrenheit. The final data set has been built selecting temperature and demand data corresponding to the available days for prices. The time series go from April 6th 1999 to March 31st 2007.

3.1 Some preliminary analysis

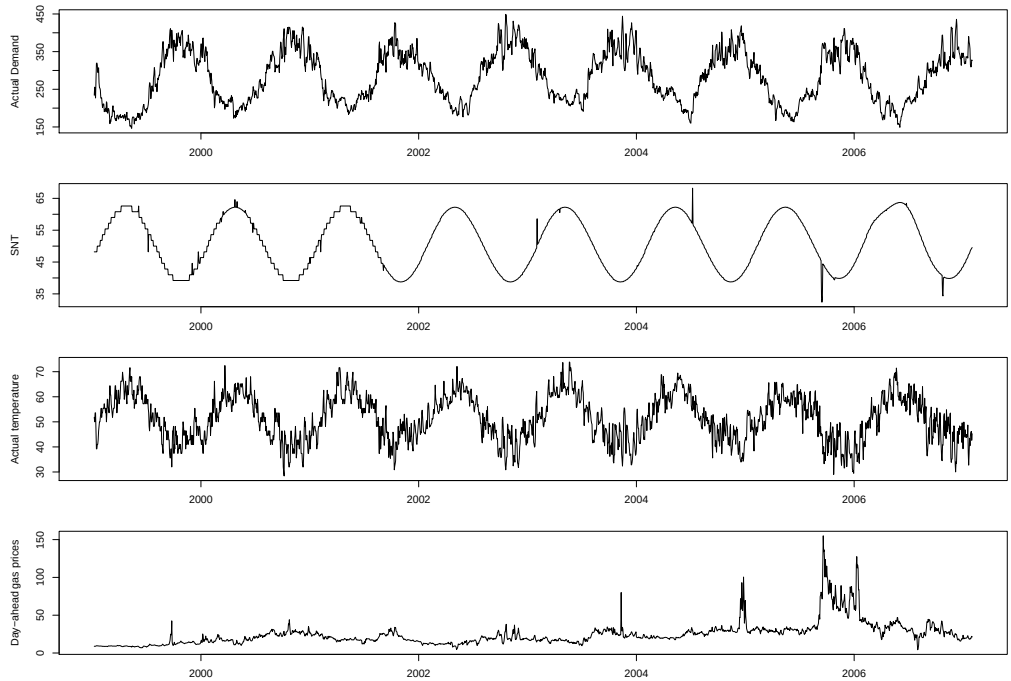
On casual inspection, it is clear that the Rough fire did have an impact on day-ahead prices for gas. Figure 4 below plots the relationship between price and temperature (with a 1- day lag), where prices for the period from the fire to one month afterwards are marked with solid circles, others with circle outlines. This casual impression is confirmed by some simple statistical analysis.

Figure 4: Prices and temperature (at time t-1) from the fire to March 2007



As a result of common latent seasonal and autocorrelation patterns across observations, regressions in terms of levels are likely to lead to spurious results, obscuring the actual link between demand and temperature. Figure 5 illustrates this problem clearly-demand and temperature, whether measured as actual or system normal temperature (SNT), exhibit complex intertemporal patterns including an annual sinusoidal path and links to the previous trading day's values. For completeness, the figure also includes the corresponding price series.

Figure 5: Demand, temperature and day-ahead prices



Therefore instead we turn to analysis of returns. Returns have been calculated as log transformation ratios of level at t and level at (t-1).[8]. The result is a percentage change (Figure 6). This transformation completely removes the seasonal component and the resulting time series are stationary according to the Phillips-Perron test (Phillips and Perron, 1988) and KPSS test (Kiatkowski *et al.*, 1992) which are reported in table 3 and table 4 respectively. It is worth noticing that the series are highly heteroskedastic (very

[8]In order to avoid problems with the logs of negative or low temperatures which occur from time to time, we adopt the convention of measuring temperature in degrees Farenheit.

evident for temperature). Hetersokedasticity will be taken into account using GARCH models for conditional variance.

Figure 6: Demand and temperature - returns

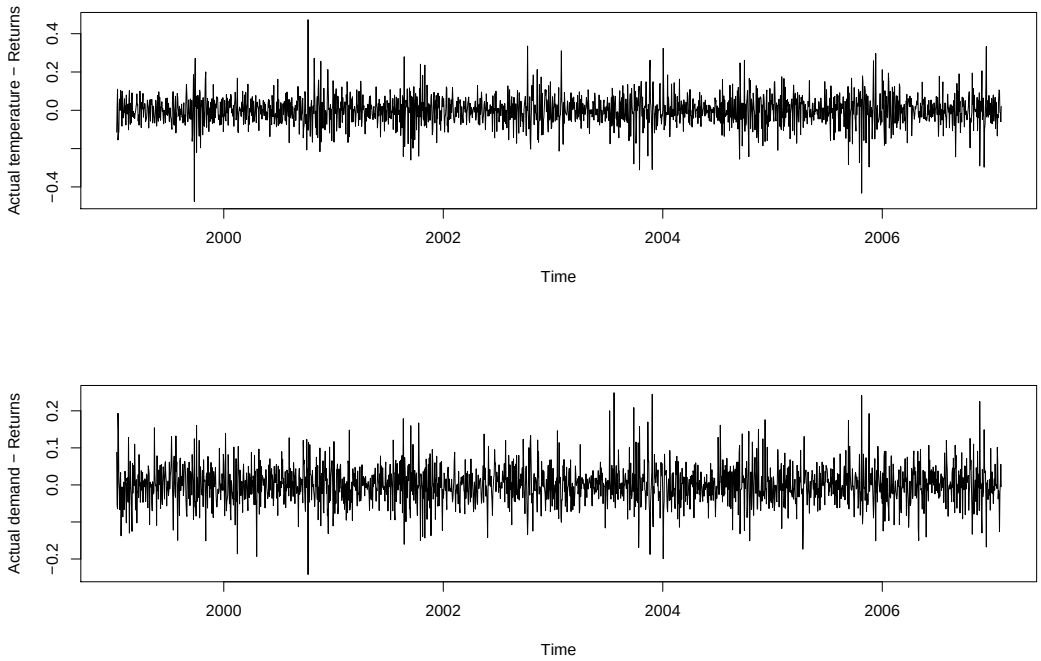


Table 3: Stationarity tests on temperature

Null Hypothesis: RTEMP has a unit root		
	Adj. t-Stat	Prob.*
Phillips-Perron test statistic	-69.21676	0.0001
Test critical values: 1% level	-3.433396	
Null Hypothesis: RTEMP is stationary		
Kwiatkowski-Phillips-Schmidt-Shin test statistic		0.017988
Asymptotic critical values*: 1% level		0.739000

We performed a Welch Two-Sample t-test of difference between means, conditional on temperature being within the post-fire period range. The null hypothesis of no difference is strongly rejected, with a t-value of 11.15 and the raw difference between means being almost exactly 50p per therm. Similarly, a Wilcoxon rank-sum test with continuity correction yielded a p-value strongly rejecting the null in favour of the alternative and a sample difference in mean of 47p.

Table 4: Stationarity tests on demand

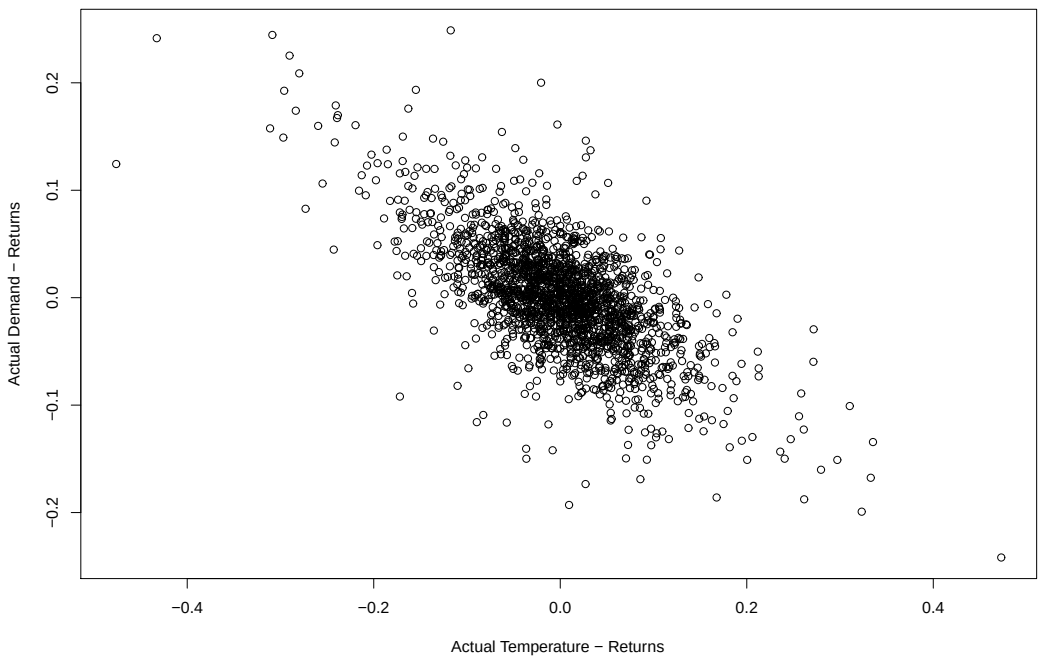
Null Hypothesis: RDEM has a unit root		
	Adj. t-Stat	Prob.
Phillips-Perron test statistic	-46.57444	0.0001
Test critical values: 1% level	-3.433396	
Null Hypothesis: RDEM is stationary		
Kwiatkowski-Phillips-Schmidt-Shin test statistic		0.018304
Asymptotic critical values*: 1% level		0.739000

These results strongly suggest an effect of the fire on day-ahead prices, both in terms of mean and (by inspection) variance. However, since there are potentially many factors at work, in the subsection below we perform some more systematic and extensive analysis on the data. Much of this involves establishing equation (1).

3.2 Testing the main hypotheses

A scatterplot of returns shows a clear strong inverse relation between demand and temperature as expected (Figure 7).

Figure 7: Demand and temperature returns - scatterplot



This relationship has been estimated by means of a linear regression with lagged values of the dependent variables to capture autoregressive effects. A dummy for a period of around one month after the rough fire is included as well. A GARCH(1,1) accounts for heteroscedasticity. Results are reported in table 5.

Table 5: Regression model of demand on temperature - returns

Variable	Coefficient	Std. Error	z-Statistic	Prob.
C	0.000148	0.000557	0.265478	0.7906
RTEMPFA	-0.481343	0.009511	-50.61075	0
DUMMY	-0.003442	0.005429	-0.633967	0.5261
AR(1)	-0.212298	0.022569	-9.406478	0
AR(2)	-0.152329	0.02455	-6.204906	0
AR(3)	-0.081395	0.026066	-3.122655	0.0018
AR(4)	-0.007693	0.024866	-0.309382	0.757
Variance Equation				
C	9.85E-05	2.50E-05	3.936491	0.0001
$RESID^2(-1)$	0.04425	0.008649	5.116475	0
GARCH(-1)	0.886262	0.022853	38.78077	0

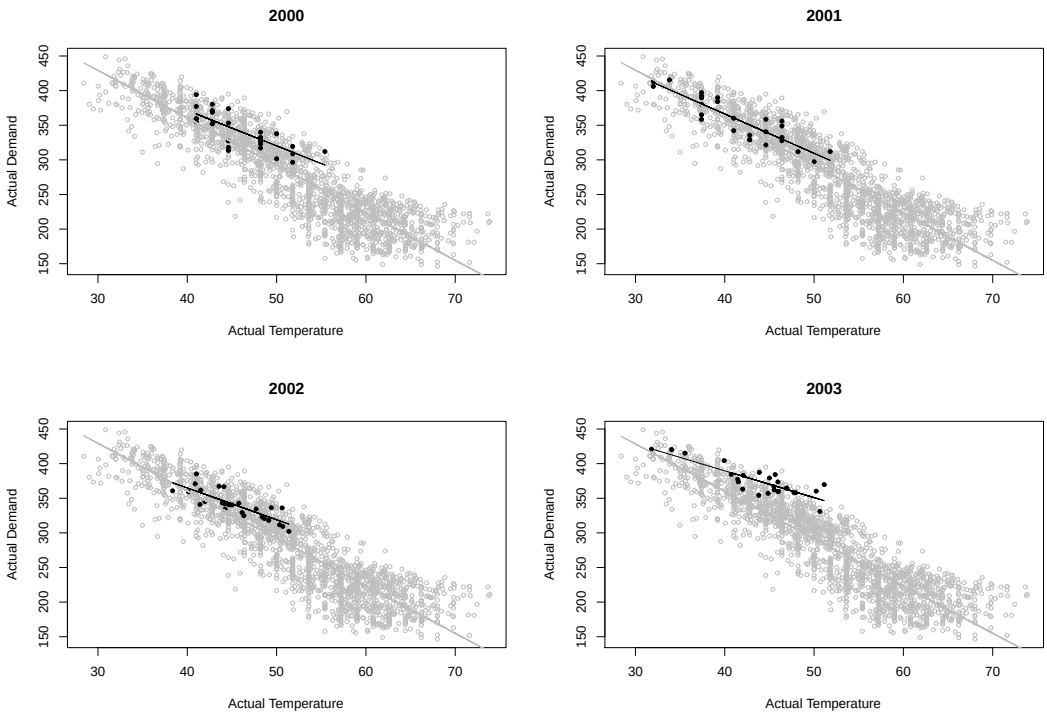
R-squared	0.470163	Mean dependent var	8.48E-05
Adjusted R-squared	0.468578	S.D. dependent var	0.052044
S.E. of regression	0.037939	Akaike info criterion	-3.725388
Sum squared resid	2.88599	Schwarz criterion	-3.697521
Log likelihood	3757.74	Hannan-Quinn criter.	-3.715159
Durbin-Watson stat	1.944887		

The coefficient on temperature returns is negative as expected and the dummy variable does not significantly affect demand variations, implying that there was no significant impact on quantity demanded except as experienced through the impact of (low) temperatures. The model is statistically acceptable because the residuals are completely whitened

and the hypothesis of residual heteroscedasticity is rejected using Engle's ARCH test. We have also tried lagged temperature returns (at time $t-1$) as explanatory variable. Results are not reported because the only significant difference is the reduction of the absolute value of the coefficient for temperature returns (-1.76), while the other coefficients are quite similar.

Nevertheless, because our result that short run demand changes are influenced solely by temperature is such a key finding, we engage in some additional analysis. On inspection, we note that the pattern of raw demand observations in the post-fire period might be considered at odds with our result in table 5. Figure 8 and figure 9 illustrate this by highlighting the immediate post-fire observations.

Figure 8: Demand and temperature - scatterplot by year:2000-03



However, inspection of the pattern over the same time period in each of the non-fire years shows very similar characteristics to the fire year, namely a uniformly shallower slope than the general relationship. A graphical examination confirms that this effect is absent from the returns regression. Table 6 reports estimates from three different regression models. In the first, daily returns obtained from demand levels are regressed

Figure 9: Demand and temperature - scatterplot by year:2004-07

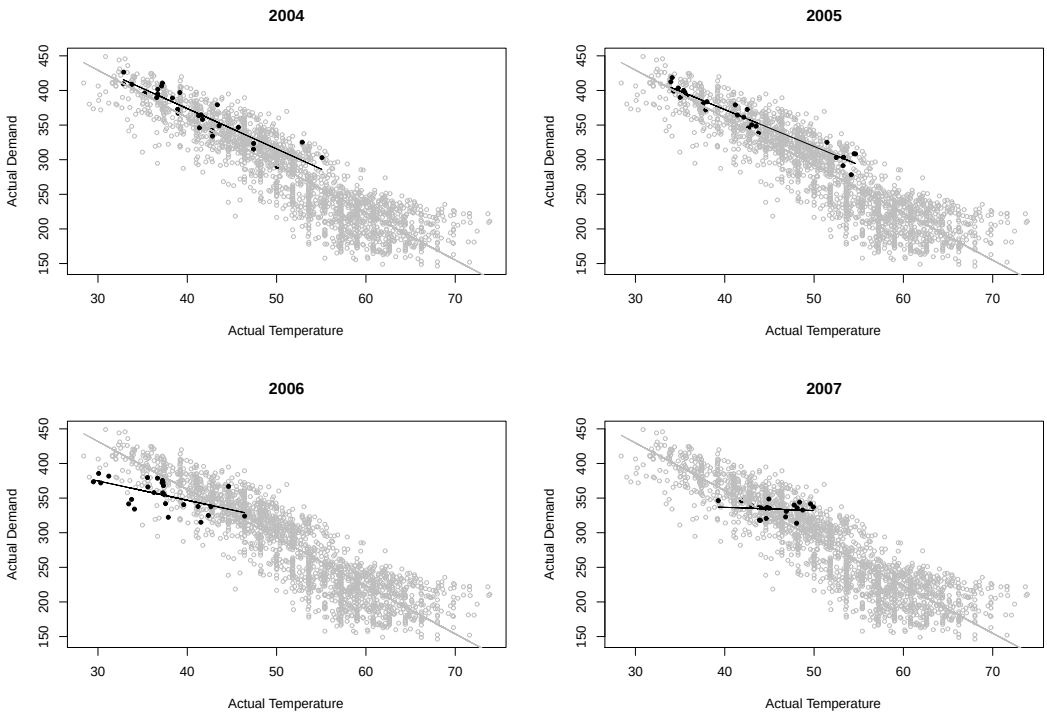


Table 6: Regression of demand on temperature: whole period and after fire

Dummy =0:	Estimate	Std.Err	t value	Pr(>|t|)
(Intercept)	0.000171	0.000871	0.196	0.844
rtempfa	-0.45124	0.011277	-40.015	0.00***
Multiple R-squared:	0.4461	Adjusted R-squared:		0.4458

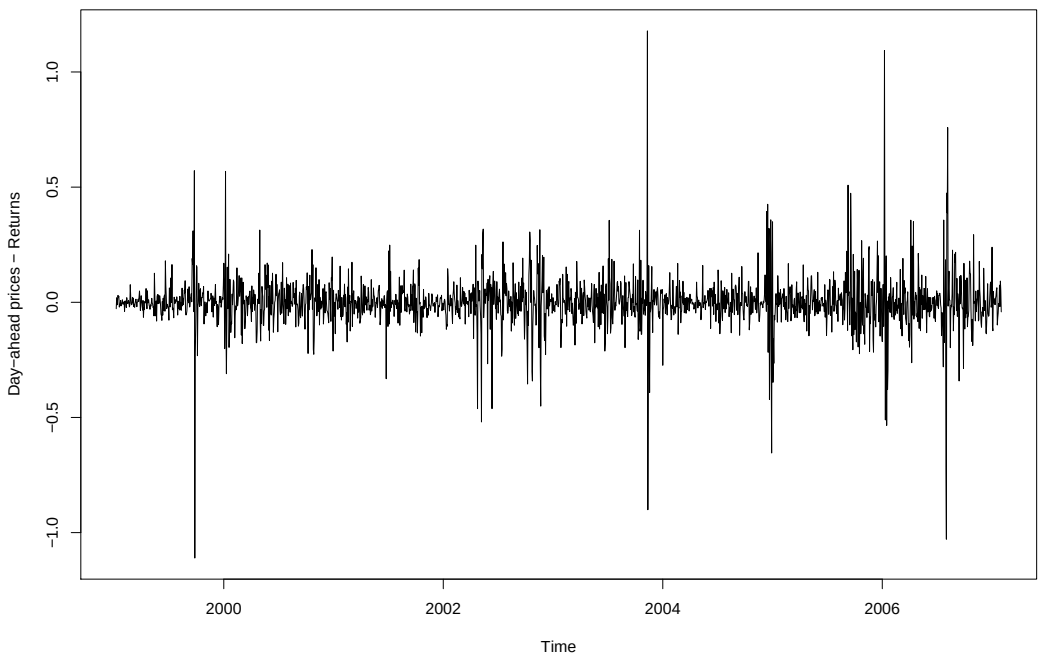
Dummy=1:	Estimate	Std.Err	t value	Pr(>|t|)
(Intercept)	-0.00433	0.006161	-0.702	0.489
rtempfa	-0.50738	0.068275	-7.431	0.00***
Multiple R-squared:	0.6971	Adjusted R-squared:		0.6844

Test for equality of the slopes:

	Estimate	Std.Err	t value	Pr(>|t|)
(Intercept)	0.000171	0.000869	0.197	0.844
rtempfa	-0.45124	0.011253	-40.099	0.00***
dummy	-0.0045	0.007691	-0.585	0.559
rtempfa:dummy	-0.05614	0.085434	-0.657	0.511
Multiple R-squared:	0.4496	Adjusted R-squared:		0.4488

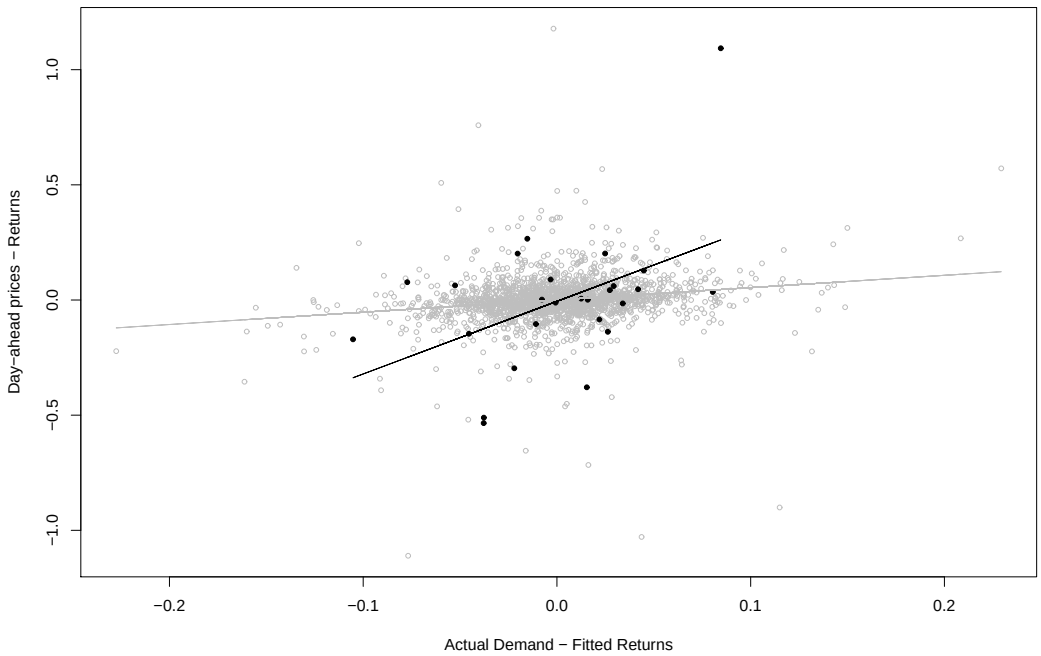
on the returns (rtempfa) computed from temperatures measured in Fahrenheit, excluding the month just after the fire. In the second, the same model is estimated only on the months after the fire. In both cases, the slopes are significantly different from zero. In the last model a dummy for the month after the fire is included, as well as an interaction term between the dummy and returns on temperature. As can be noticed the last term is not significant, meaning that the slopes cannot be considered significantly different. Hence, we consider this to be a seasonal effect rather than the impact of the fire. This is important since it confirms the exogeneity of prices with respect to demand in the short run.

Figure 10: Day-ahead prices - Returns



Having established equation (1), we now turn to estimating the system (9) and (10), that is to see the nature of the impact of the fire on the supply relationship. To do this we take the fitted values of Demand returns (RDEMF) from the previous model and used these to explain day-ahead price returns (Figure10). Figure 11 reports that the scatterplot of the variables exhibits a positive relationship as expected and illustrates the clear difference in the relationship between the general run of observations and the

Figure 11: Demand fitted returns and day-ahead prices - scatterplot



post-fire period, in particular the slope. Model estimates are reported in table 7.

Table 7: Regression of fitted demand on prices: whole period and after fire

Dummy =0:	Estimate	Std.Err	t value	Pr(>|t|)
(Intercept)	0.000408	0.002329	0.175	0.86
rdemf	0.533924	0.062729	8.512	0.00***
Multiple R-squared:	0.03523	Adjusted R-squared:		0.03474

Dummy=1:	Estimate	Std.Err	t value	Pr(>|t|)
(Intercept)	-0.00575	0.053312	-0.108	0.915
rdemf	3.153248	1.232916	2.558	0.0173*
Multiple R-squared:	0.2142	Adjusted R-squared: 0.1814		

Test for equality of the slopes:

	Estimate	Std.Err	t value	Pr(>|t|)
(Intercept)	0.000408	0.002409	0.17	0.865
rdemf	0.533924	0.064887	8.229	0.00***
dummy	-0.00616	0.021197	-0.29	0.771
rdemf:dummy	2.619323	0.49134	5.331	0.00***
Multiple R-squared:	0.05178	Adjusted R-squared: 0.05036		

The coefficient of Fitted Demand returns is positive and significant, as expected. Most importantly for our modelling framework, the Rough fire dummy variable seems to influence sensitivity of demand returns to price returns.

The straightforward interpretation of these results is that the fire has impacted on the nature of the supply relationship, forcing a move to alternatives to Rough with attendant problems of higher prices and less certain outcomes. The main remaining issue with this model is the very poor goodness of fit, together with the presence of an outlier in the data for the fire period. The plot also suggests an increase in variance of returns. Hence we engage in some sensitivity analysis, along with consideration of the amended modelling framework in equations (11) and (12) .

4 Sensitivity analysis

4.1 Formal procedure

In order to evaluate the effect of fire on the relation between day-ahead prices and forecast demand in greater depth, a sensitivity analysis was carried out using a rolling window technique. The analysis aims to check that the differences in slopes and in the residuals variance has not been observed in periods other than in the immediate aftermath of the fire.If we are right and the effects we have observed are a result of the fire, then we should expect the window to pick this event out in the data, even if we were not to know its timing.

The procedure is straightforward and depends on some simple choices: the length of the period to analyze and the window size. Let Y be the price returns time series and X be the time series of forecasted returns on demand. Let L be the length of the period we want to analyze, w be the window size and T be the length of the original time series. The length L will be centred on the date of the fire t_f.

The method we introduce is iterative. In the case of each iteration we compare two sets of observations: the subset containing the majority $(T - w)$ of the units, called the "majority set" and the subset containing w observations, called the "minority set". The

main steps of the procedure are summarized in the following list.

- At the first iteration the majority set is given by the $(T-w)\times 2$ matrix $Z^{ma} = (Y^{ma}, X^{ma})$. The generic row of Z^{ma} will be $z_t^{ma} = (y_t^{ma}, x_t^{ma})$, with $t = 1, \ldots, (t_f - L/2), (t_f - L/2 + w + 1), \ldots, T$. The minority set is given by the $w \times 2$ matrix $Z^{mi} = (Y^{mi}, X^{mi})$ whose generic element is $z_t^{mi} = (y_t^{mi}, x_t^{mi})$, with $t = (t_f - L/2 + 1), \ldots, (t_f - L/2 + w)$.

- At the second iteration the window is moved forward by one step so that $t = 1, \ldots, (t_f - L/2 + 1), (t_f - L/2 + w + 2), \ldots, T$ for the majority set and $t = (t_f - L/2 + 2), \ldots, (t_f - L/2 + w + 1)$ for the minority set.

- ...

- In the last iteration the window is moved forward by w steps, that is $t = 1, \ldots, (t_f + L/2), (t_f + L/2 + w + 1), \ldots, T$ for the majority set and $t = (t_f + L/2 + 1), \ldots, (t_f + L/2 + w)$ for the minority set.

At each iteration three different models are estimated:

$$y_t^{ma} = \beta_0^{ma} + \beta_1^{ma} x_t^{ma} + \varepsilon_t^{ma} \tag{13}$$

$$y_t^{mi} = \beta_0^{mi} + \beta_1^{mi} x_t^{mi} + \varepsilon_t^{mi} \tag{14}$$

$$y_t = \beta_0 + \beta_1 x_t + \beta_2 D_t + \beta_3 (D_t x_y) + \varepsilon_t \tag{15}$$

where D_t is a dummy variable such that $D_t = 1$ if $t = (t_f - L/2 + i + 1), \ldots, (t_f - L/2 + w + i + 1)$ and $D_t = 0$ if $t = 1, \ldots, (t_f - L/2 + i), (t_f - L/2 + w + i + 1), \ldots, T$, with $i = 1, \ldots, L$.

We are interested both in comparing the slopes of models (13) and (14) and how observations are spread around the corresponding regression line. Looking at Figure 11 we want to explore if the slope of the black line is significantly greater than the slope of

the grey line and if the dispersion of black points around the black line is greater than the dispersion of grey points around the gray line. The first hypothesis can be formalized as follows:

$$H_0 : \beta_1^{ma} = \beta_1^{mi} \qquad\qquad H_1 : \beta_1^{ma} < \beta_1^{mi} \tag{16}$$

The hypothesis in (16) means that the reaction of prices variations to demand changes has increased after the fire.

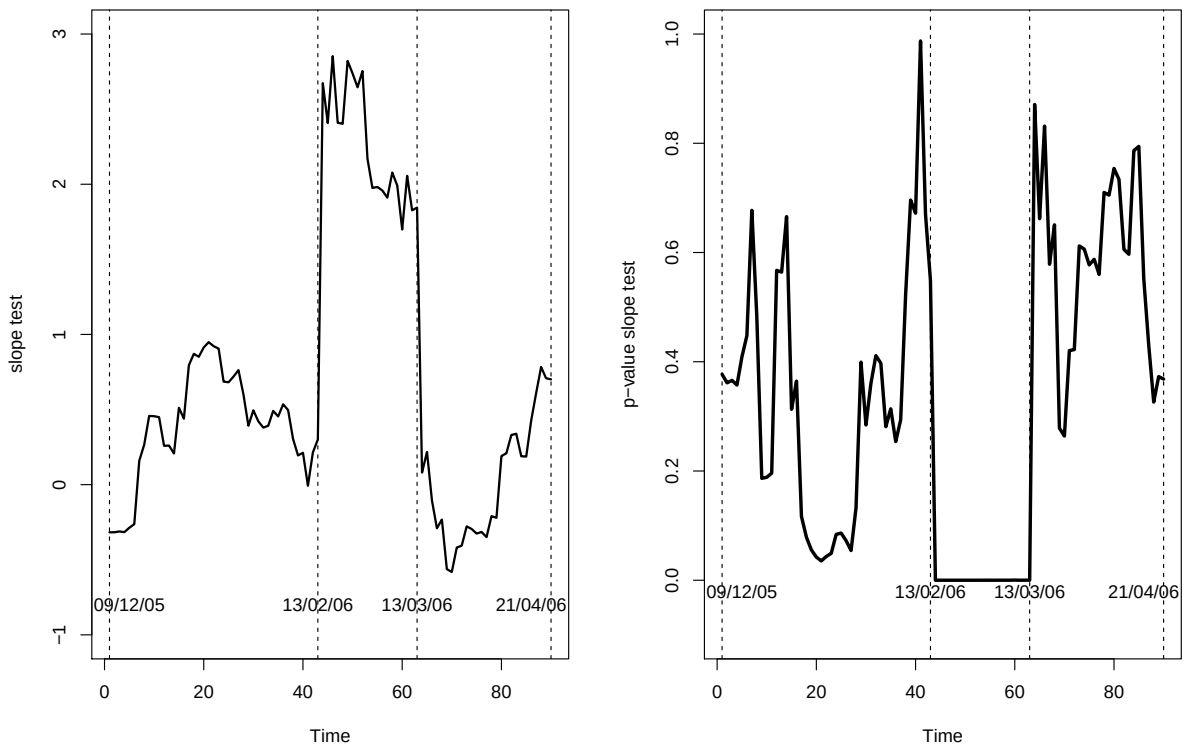
The second hypothesis can be formalized as follows:

$$H_0 : \frac{\sigma_{mi}^2}{\sigma_{mi}^2} = 1 \qquad\qquad H_1 : \frac{\sigma_{mi}^2}{\sigma_{mi}^2} > 1 \tag{17}$$

where $\sigma_{ma}^2 = \sum(\varepsilon_t^{ma})^2/(T-w)$ and $\sigma_{mi}^2 = \sum(\varepsilon_t^{mi})^2/w$ are the residual variances of model (13) and of model (14). respectively. The meaning of hypothesis (17) is that volatility, and thus uncertainty, of the price-demand relationship has increased just after the fire. Hypothesis (16) can be tested by means of a t-test on the parameter β_3 related to interaction term in (15). This is a classical example of covariance analysis. The second hypothesis should be tested using the classical F-test for comparing the variances of two samples from normal populations. We used the R-function `var.test`. As the distribution of the two samples does not perfectly fit a normal distribution we also applied an asymptotic test for dealing with possible violation of the Gaussian assumption (Coeurjolly *et al.*, 2009). The R-function used in this case is `asymp.test` within the R-library `AsympTest`. However, the results from the two types of test were very similar.

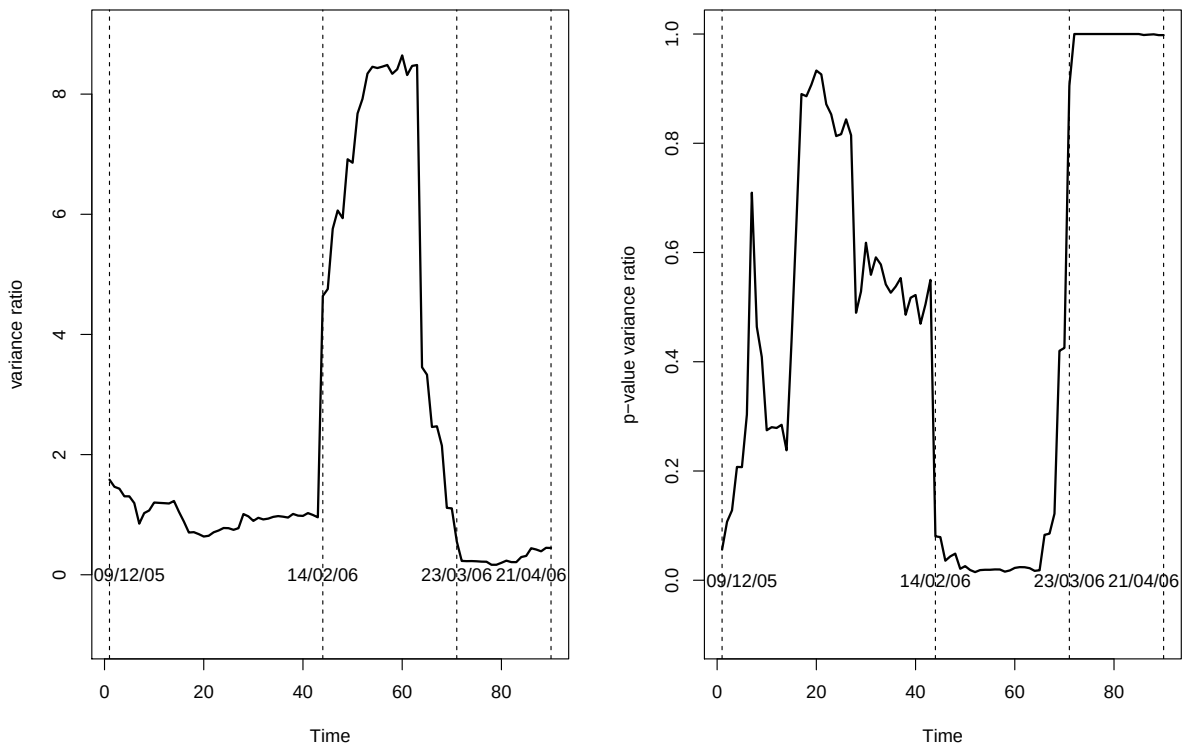
The output of the sensitivity analysis is reported in Figure 12 and Figure 13 with $w = 20$ (the approximate number of trading days in a month) and $L = 90$. Figure 12, left panel, reports the values of the statistic-test obtained when testing the difference in the slopes between the two subsets of observations while in the right panel of the same figure the corresponding p-values are reported. When the p-value is close to zero the null of

Figure 12: Test for the equality of slopes (left panel) and corresponding p-value (right panel). Window length $w = 20$, number of iterations $L = 90$.



equal slopes is rejected. From this figure we can see that when the window starts covering the period immediately after the fire (16 February 2006) a big jump is observed which then disappears around one month after the fire. The positive sign of the test means that during this period the slope of the minority subset was always greater than the slope of the majority and consequently the reaction of prices to demand has been stronger. Figure 13, left panel, reports the values of the ratio between the residual variance of the model estimated on the minority set and the residual variance of the model on the majority set. The right panel of Figure 13 reports the corresponding p-values for the hypothesis of equality of variances. Again, a jump is observed when observations after the fire are included in the minority subset and the effect disappears around the end of March. This means that following the fire a higher volatility in returns has been observed, presumably

Figure 13: Test for the equality of residual variance (left panel) and corresponding p-value (right panel). Window length $w = 20$, number of iterations $L = 90$.



connected to higher uncertainty on the market.[9]

In sum, in addition to the increased sensitivity to prices, customers for gas also faced more volatility in prices as a result of the fire. The fact that our sensitivity analysis picks out quite clearly the key period in the immediate aftermath of the fire is, for us, powerful evidence that the effects we observe are a result of the Rough fire, not some alternative chance event taking place at a similar time.

5 Conclusions

Our analysis strongly suggests that despite almost the most severe possible test of resilience conceivable at the time, demand in the UK gas system was not measurably

[9] We also experimented with dropping the outlier observation, although there was no underlying reason so to do. The variance relationship survives this exclusion, although the mean effect is weakened.

impacted by the outage of the Rough storage system. However there was, literally, a price to pay, in that gas prices moved significantly above what they otherwise would have been, showing a much greater sensitivity to temperature. If this were to have been the only impact, then it could be hedged against by financial means, rather than physical storage. In other words, rather than storage providing the insurance, hedging contracts could do so. What may be rather more difficult to counter is the substantially increased volatility in prices (measured as returns) during the key window that we observed in section 4, which renders production planning difficult in facilities where gas is a key part of the production process. Of course, since then there is less "swing" capability in the gas production facilities, a result of declining gas fields off the UK coastline. However, nothing in the incident we have examined suggests the gas storage situation in the UK is dire.

6 Appendix 1: A note on the cost of gas storage

There is a question of what to compare the impact of the Rough fire with. It clearly had costs on the economy, due to higher and more volatile prices. However, developing and using such storage facilities is not free. If the UK had had additional storage, for this period, these problems could have been prevented, but this storage would have been expensive. It seems most logical to attempt to compare the daily costs to consumers of the higher prices they paid with the costs of renting such storage for an equivalent period.

The rental costs are assumed to be the annual charge on a hypothetical storage facility capable of supplying an equivalent amount of working gas. These (long term storage) facilities are used on a basis of inputs in the Summer months and outputs during cold spells in the winter, so most of the earnings take place over a very small part of the year. The Competition Commission (2003,fig.4.3) implies Rough is marginal for approximately 25 days in an average year and would be used as a supply source for an average of around 50 days per year.

There follows a very casual assessment of the costs of developing and operating such a facility.

From the viewpoint of cost, as a result of commercial confidentiality it is difficult to get accurate costs of constructing a storage facility. However, at least two ballpark figures are available. The first is from the Federal Energy Regulatory Commission (2004), which gives the development costs per billion cubic feet (bcf) of working gas capacity as between $5mand12$m upwards, dependent upon type, with the costs of 2-cycle reservoirs towards the bottom of this range. There is then the cost of "cushion gas", required in the facility in order for it to operate successfully, but which is not part of the working gas. For a 2-cycle facility based on a depleted field, gas equivalent in volume to the working gas capacity would be required. A more recent estimate comes from a short prospectus arising from the prospective sale in mid 2011 by Continental Gas Storage BV of its German subsidiary to Haddington Ventures LLC. The equivalent development cost here of the final project amounts to around $27m per bcf, for a salt cavern facility.[10]

[10]This is said to be the first independently owned and operated gas storage project in the EU. Salt

Rough's maximum daily outflow when in operation is said to be around 45 million cubic metres a day (Competition Commission (2003) Table 4.1, gives it as 455GWh/d or 1.55bcf/day, which tallies closely with this). Over the period of around 1 month following the fire, prices were around 50p per therm above normal. This is equivalent to £5m per bcf (a therm being 100cuft). A typical day at this time of year involves consumption of around 350mscm (million standard cubic metres) that is 12.36bcf. So the excess charge amounts to around £61.8m per day, or £1.854bn over the month, assuming all gas traded at that higher price. However, if this was only the marginal price on the input that would otherwise have come from Rough, with the remainder of gas being on longer term contracts at "normal" prices, then the excess charge would be around £8m per day, or £239m for the month. Rough's capacity is said to be 3 billion cubic metres (Competition Commission (2003), Table 4.1, gives it as 30,344GWh, or 103.5bcf). At current costs, an equivalent facility would involve development costs of say $10m (or £6m) per bcf, which is £636m for the facility of equivalent size. With cushion gas costs of say 35p per therm (available in Summer 2005), cushion gas would add £362m to the development costs of the project. Hence the total project costs would probably be in excess of £1bn, requiring a return of say £150m per annum over a short period. To this should be added running costs. So on this basis Rough's outage cost is commensurate in size with the cost of having an alternative facility.

caverns require more cushion gas but can cycle several times over the year.

7 Appendix 2: Detailed timeline of announcements on the Rough fire(significant points only)

All the following are sourced directly from the Centrica news website for the given dates.

At around 10:30 this morning, Thursday 16th February, 2006, there was a small fire on the 3B Rough offshore platform. The fire has been put out. There were two casualties who have been evacuated by helicopter to hospital. We understand that their injuries are minor. As a precaution we have reduced manning on the 3B platform to essential levels. The remainder of our 3B personnel have been safely evacuated. The platform has been de-pressurised and made operationally safe.

Update on the Incident at the Rough facility on Thursday 16th Feb 15.00 Incident at the Rough Gas Storage Facility

Centrica Storage Ltd. confirms that there has been an incident at its Rough Offshore gas storage facility. As a result, all operations have been suspended until further notice.

February 17, 2006 - 10:00 Declaration of Force Majeure on 16th Feb 2006 We hereby give you notice that under the terms of the Storage Services Contract currently in force we notify an occurrence of Force Majeure. February 20, 2006 - 14:00 Update on Incident At Rough on the 16 February 2006 Over the weekend inspection of the Rough platform began... Following this initial visual inspection we currently estimate that it is unlikely that Rough will be available for one month. We would emphasise that this is an initial estimate pending a thorough investigation and further updates will be made in due course.

February 24, 2006 - 12:00 Update on Rough Incident Our initial estimate that Rough is unlikely to be available for one month remains unchanged. We would re-emphasise our statement of 20th February that this estimate is based on a preliminary assessment of the scene and is subject to change. By the end of next week (3 March 2006) we hope to be in a position to report further on our recovery plans. March 1, 2006 - 14:00 Force Majeure Update on 01 March 2006 Further to our update notice of 24 February 2006 ... our initial assessment of the site has revealed that a significant amount of the cabling in the vicinity of the fire has been damaged ... we now estimate that the Rough facility will

be unavailable for both injection and production until at least 1st May 2006. March 10, 2006 - 15:00 Based on our current state of knowledge as to the extent of the damage at this time, we still estimate that the Rough facility will be unavailable for both injection and production until at least 1st May 2006. March 24, 2006 - 14:00 Our current best estimate of the date of resumption of injection operation is 1st June 2006, although this remains subject to change.

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