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Energy Sustainability

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REVENUES FROM STORAGE IN A COMPETITIVE ELECTRICITY MARKET: EMPIRICAL EVIDENCE FROM GREAT BRITAIN *

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ABSTRACT: Despite the high upfront financial costs associated with the existing technologies for energy storage they have become more appealing in recent years in response to the increasing importance of non-dispatchable sources of generation in the energy systems of developed countries. One of the essential pieces of information required to value the monetary benefits which can be achieved when investing in energy storage is the price that energy will command when it is released, compared with the price paid when injected into the storage. In this paper we investigate this relationship using time series statistical techniques for various maturities of forward prices, using data on assessments of power prices for future delivery. We will examine the relationship for predictability and size of gap in order to answer questions about the likely financial benefits which can be obtained from optimal time management of storage facilities, using a technology neutral approach. Our initial results indicate that such arbitrage opportunities exist for storage facilities, especially when energy is stored over a short-term period of a day or a week.

JEL Codes: L11, L94, G13, C58, G17

Keywords: Energy storage, wholesale electricity markets, electricity price returns, volatility, arbitrage

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1. Introduction

The legally binding commitments of several developed countries to achieve reductions in carbon emissions and the concerns about the potential dependence on foreign sources for energy supplies has led many countries to invest in renewable technologies which are likely to become more widespread in the near future. In addition to the substantial investment costs associated with these technologies their integration in the electricity system generates further system-wide costs in order to meet the need for back-up generation, due to the intermittent nature of the output from some renewable sources. Recently developed technologies for electricity storage can offer an alternative to building and operating additional peaking generation plants to deal with intermittent supply, provided that sufficient revenues can be raised from operating the storage facilities (Byers, 2006). These revenues are required in order to compensate investors for the costs and risks associated with installing the storage facilities and integrating them into the existing energy system.

There are many papers that consider the issue of energy storage within a broadly economic framework, commonly with a particular institutional background in mind. Examples which rely on an explicitly economic framework include Greenblatt et al (2007), Dufo-Lopez et al (2009), Sioshansi et al. (2009), Sioshansi (2010) and Xian and Zachmann (2010). These papers address a range of issues, but one of the key aims is to analyse the impact of storage on prices; another is to evaluate the profitability of storage (or potential profitability given particular build costs). The main impact of storage is to smooth prices, or thinking of it from the storage point of view, the main revenue stream analysed in the literature is essentially power arbitrage. This is commonly connected with making use of (and potentially adding value to) wind or solar power which is not biddable, with storage making it more biddable and hence making money through time shifting to more highly priced periods (arbitrage). Some of the models in the literature make the assumption that the storage facility is price-taking, while others assume that it is large enough to have an impact on prices. In this paper we assume a price-taking storage facility, as we have no empirical evidence about the effect on wholesale prices of the emerging storage technologies, which have different technological features compared to the more established pumped hydro storage technology.

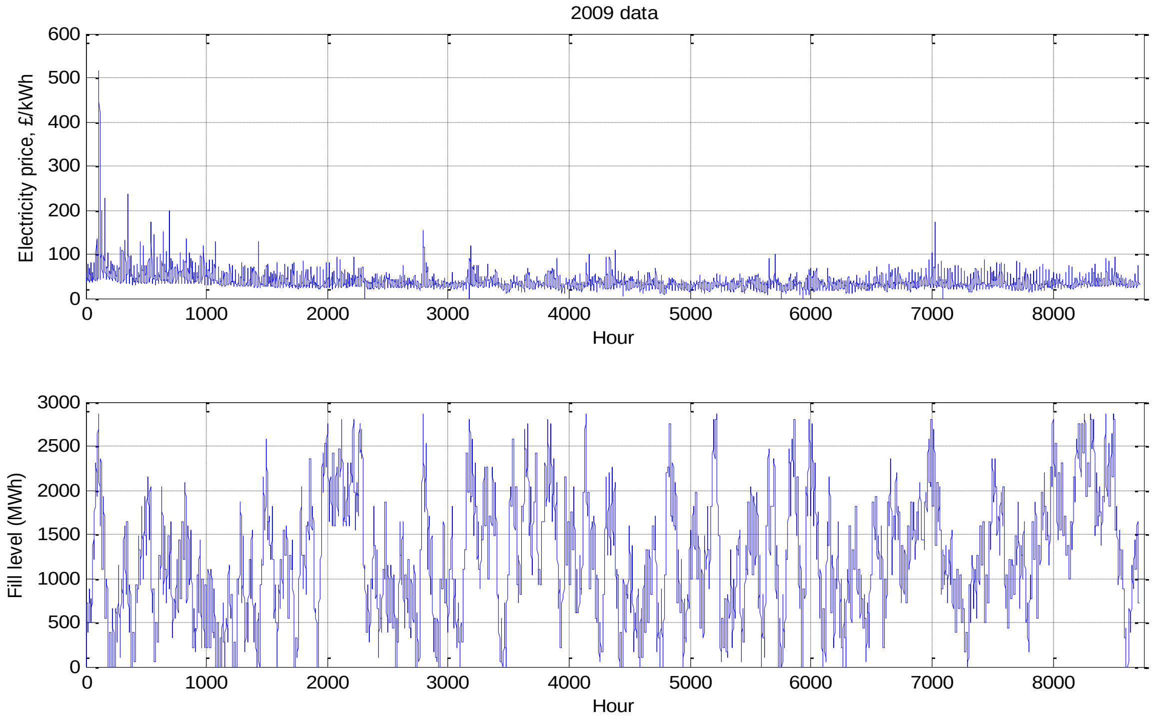
Two widely-adopted features of these models characterise the majority of the papers mentioned above. The first is that the models almost universally assume perfect foresight in power prices. The second is that they use a simulation framework to analyse the model´s implications. The first is an optimistic assumption regarding the benefit of storage, since without perfect foresight there will be opportunities that will not be apparent at the time, while opportunities that are taken may turn out not to have been timed optimally. Using this type of framework Sioshansi et al. (2009), claim that 2-week back-casting will enable approximately 85% of benefits to be achieved. As for the adoption of a simulation framework, although this may be inevitable given the complex interdependencies in the energy system, the main limitation of this approach, as opposed to an analytical framework, is that where results differ between papers, the underlying reasons for the differences are opaque. Indeed the simulation models inevitably imply a loss of generality and comparability across alternative scenarios.

Despite the relatively abundant work in the area, there still seems to be a significant role for investigation of the time series properties of price series and relationships between them, for example, between today’s off-peak prices and tomorrow’s peak prices. Furthermore, investigations which rely on an analytical approach to modelling the storage operator’s problem are relatively rare in the literature, however such approach would make it possible to characterise solutions in terms of key parameters and their influence on the outcome, for example the profitability of storage operation. This paper aims to generate a first contribution in this direction by taking an analytical approach to the problem of storage profitability and relating the predicted outcomes to the empirical evidence generated by the time-series analysis of wholesale price data.

One of the essential pieces of information required to value, in monetary terms, the benefits which a private (or public) investor can achieve from investing in energy storage (for example, compressed air, but the principle is the same whatever the chosen technology) is the price that energy will command when it is released (discharged), compared with the price paid when injected into the storage, i.e. when charging the storage facility (Byers, 2006, Carmona and Ludovski, 2010). This assumes that arbitrage is the only source of revenue from storage and ignores other possible revenue streams, such as the revenues from transmission and distribution network operators or from Government managed capacity markets. In this paper we investigate this relationship using time series statistical techniques for various maturities of forward prices, analysing data on assessments of future power prices. We will examine the relationship in order to answer questions about the likely financial benefits which can be obtained from optimal intertemporal arbitrage using storage facilities.

An illustrative example of the activity associated with this type of arbitrage exploitation is provided in Figure 1 below, which exemplifies the arbitrage opportunities arising over a 24-hour period, on the basis of information about the hourly spot prices observed in the UK, for the year 2009. The top part of the figure contains the historical price series for the electricity spot price (source Elexon) while the lower part of the figure results from a simulation of the fill levels calculated for the McIntosh CAES plant in Alabama, USA. The results are derived from a simulation exercise discussed in more detail in Garvey and Pimm (2012) where it is assumed that the storage facility can react without delay to the price signal provided by the spot electricity market. In this work it is also assumed that the spot price provides a reliable signal about the ´value of electricity´ at a given point in time, an assumption which could be challenged on the grounds that the UK does not have a compulsory spot market (as known as ´Pool´ market) and that the trade carried out in the voluntary spot market represents a small minority of the energy trade going on in the wider market.

Figure 1: Hourly spot power prices for the UK (2009) and simulated fill levels for CAES plant



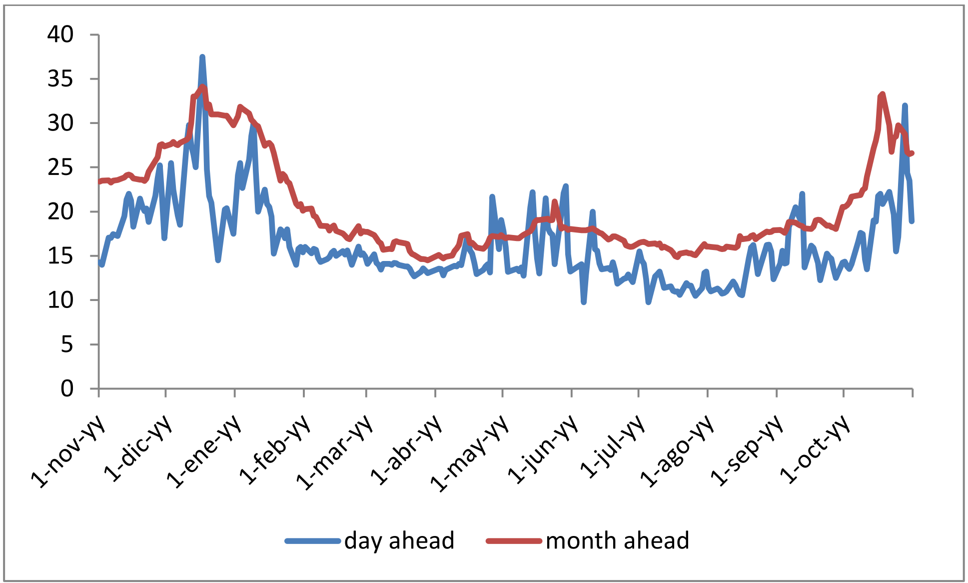
Source: Garvey and Pimm (2012).

Relying on the exploitation of spot market fluctuations for the storage facility's future revenue flow involves a high level of financial risk for the owner of the storage facility. To avoid the revenue risk associated with short term fluctuations in the spot market, the owner of a storage facility can potentially "lock in" the benefits of low energy prices by carrying out a simultaneous transaction, buying power when it is cheap and backing that contract with a contract to sell that power (minus the losses in conversion etc.) at some future period, say one week or one month later. This behaviour de-risks the investor in storage from the wildly fluctuating energy prices which modern power markets experience, enabling them to focus on the technical operations of the plant.

Therefore an important series of issues, when assessing storage profitability, relate to the magnitude and statistical properties of the price distribution at any point in time. More specifically, the question is whether the relationship between spot and future prices at any point in time exhibits a behaviour that can be statistically characterised in straightforward ways, enabling further analysis to build on this approach, or whether the relationship contains too high a noise to signal ratio to be useful.

An illustrative example of the arbitrage opportunities which can arise in the futures markets is provided in Figure 2, where arbitrage opportunities can be observed in the periods around December 24th 2001 and October 18th 2002, when comparing the price for day-ahead and month-ahead contracts (source: Platts).

Figure 2: Example of arbitrage opportunities in futures electricity markets



However, in order to assess the profitability of a storage facility in practice it is necessary to compare the potential revenues from inter-temporal arbitrage in the forward market with the round-trip efficiency of alternative storage facilities, i.e. the amount of power which can be retrieved when extracting power from the storage facility (discharging)[2].

In this paper, in addition to the statistical analysis of the price differences for electricity to be delivered at different maturities, we will calculate the proportion of days when a positive revenue can be obtained in the presence of alternative theoretical values of round-trip efficiency, using values which can be considered as realistic and feasible for a range of alternative storage technologies. The next section describes the data and methodology which will be used in the analysis. Section 3 will cover our initial results from the statistical analysis of revenues from alternative future contracts. Section 4 presents an attempt to model extreme observations in the price data and in our index of storage profitability. Section 5 concludes with a discussion on the future direction of research.

2 "Various physical properties can be used to store energy and eventually change it to electricity. The conversion from electrical energy to stand and back has an "overhead" associated with it, and the round trip efficiency of the system should be analyzed. Round trip efficiency is defined as:

$$\frac{\text{Energy received at the grid on the primary side of the transformer}}{\text{Energy sent from the Grid on the primary side of the transformer}}$$

This calculation of efficiency is critical to the economic evaluation of electricity storage systems. Basically, what doesn't come back to the grid must be paid for in some manner."
(Source: US Electricity Storage Association http://www.electricitystorage.org/technology/about_energy_storage/energy_storage_physics)

2. Data and Methodology

The empirical analysis of an hypothetical storage facility is based on data on power prices and power futures assessment for Great Britain which have been obtained from Platts UK's Powermarkets dataset. The time horizons for which we have information are: day-ahead, week-ahead, month-ahead. However, due to the technical characteristics of electricity storage, i.e. the limited amount of energy which can be stored at any facility, we will focus only on a time horizons of a week and a month-ahead to reflect the predominantly short term nature of electricity storage. The variables used in the analysis are listed as follows:

For the electricity market:

- Day ahead base load assessments, for delivery from 23:00 the day of trade until 23:00 the day after.

- Day ahead peak assessments, for delivery 07:00-19:00 the day following trade.

- Week-ahead peak assessment, for delivery each day Monday-Friday the following weeks.

- Month-ahead peak assessments. UK EFA months are comprised of four- and five-week blocks. They follow the pattern 4-4-5, meaning March, June, September and December have five weeks and other months have four.

For the gas market:

- Day-ahead assessments: delivered next working day after assessment; for instance, Friday's assessment reflects Monday delivery, including bank holidays when the price will often be close to the weekend price.

- Working Days Next Week (WDNW) assessments: prices are for flat gas to be delivered throughout every working day in the week following the date of the report, i.e. contiguous working days following the next Weekend period.

- Month-ahead assessments: Monthly prices represent flat gas to be delivered at a flat rate throughout each day of the month, beginning at 06:00:00 on the first day of the month and ending at 05:59:59 on the first day of the succeeding month.

The data are at daily frequency (working days only) are available from 26th March 2001 for the electricity market and from January 1997 for gas market. Electricity prices are measured in GBP/MWh, while gas prices are measured in UK pence/therm.

In the first stage of the analysis we focus on the weekly seasonal pattern of prices. Different seasonal pattern across different contract maturities could reveal different opportunities to gain from arbitrage activity.

Two statistical approaches have been applied to study weekly seasonality:

- Estimation of AutoRegressive models with weekly seasonality (5-day seasonality);
- Estimation of linear regression models with day and month dummies.

Both models can be properly applied only to time series generated by non-integrated stochastic processes. Thus, we preliminary apply stationary tests for the presence of unit roots: Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test (which is based on the null hypothesis of stationarity) and Phillips-Perron (PP) test (which is based on the null hypothesis of unit root). The results for these stationarity tests are reported in Table 1 for the electricity prices and in Table 2 for the gas prices:

Table 1: Stationarity tests (original series - electricity)

	Day ahead base load	Day ahead peak	Week ahead peak	Month ahead peak
KPSS test statistic	0.2482	0.2587	.2637	0.2611
Test critical values (1% level)	0.216	0.216	0.216	0.216
Phillips-Perron test statistic	-6.4705	-7.4826	-4.5964	-3.1008
Test critical values (1% level)	-3.968	-3.968	-3.968	-3.968

Table 2: Stationarity tests (original series - gas)

	Day ahead	Week ahead	Month ahead
KPSS test statistic	0.3505	0.3637	0.3484
Test critical values (1% level)	0.119	0.119	0.119
Phillips-Perron test statistic	-5.912	-4.973	-2.899
Test critical values (1% level)	-3.968	-3.968	-3.968

In our preliminary analysis of the time series properties of the variables of interest we have explored alternative ways to analyse this kind of non-stationarity:

1) Original time series were de-trended by the estimation of smoothed-spline. Then AR and regression models were estimated on the distance from the estimated splines.
2) Fractional integration models were estimated directly on price settlements with inclusion of autoregressive parameters and dummy variables.

Both approaches gave results in accordance to the previous models discussed above, demonstrating the robustness of the procedure.

As a result of this set of stationarity tests the presence of unit root could not always be rejected both for electricity and gas market. For this reason we move from prices levels to log-returns on prices, computed as log[p(t)-p(t-1)], which is a transformation used for the time series analysis of arbitrage opportunities discussed in section 3.

3. Initial analysis of arbitrage opportunities

In order to evaluate the potential revenues from operating a storage facility at different time horizons we calculate what we define as a 'park' spread which measures the profitability (in percentage terms) of storing power purchased at a given date t and sold on the same date via a contract signed at time t for delivery at time t + N:

$$\textit{Future price } (t, t+N) - \textit{day-ahead baseload } (t) \,/\, \textit{day-ahead baseload } (t)$$

where the day-ahead price is associated with base load power and the future price refers either to base load or to peak power, in which case we are assuming that the owner of the storage facility aims to exploit fully the arbitrage opportunities offered by the ability to discharge power at any given time in the future.

A first stage in the analysis of the financial viability of the arbitrage opportunities which arise from exploiting the peaks and troughs of the future electricity markets involved comparing the estimated level of revenues from this form of arbitrage (using a time horizon of a week and a month) with the alternative levels of round-trip efficiency associated with the existing types of storage technology. This allows us to calculate the proportion of observations identifying the days when it is possible to obtain positive revenues for a chosen level of round-trip efficiency. In our initial analysis we have selected only two 'realistic' levels of round-trip efficiency for electricity storage: 60% and 70%.

Our initial results on the potential profitability of storage facilities with different levels of round-trip efficiency indicate that, when buying and selling base load power, positive revenues can be obtained with round-trip efficiency at the 60% and 70% level, although positive results tend to be concentrated in the years between 2005 and 2008 (see Tables 4 and 5). If the contract for future delivery refers to peak power then the positive revenues are observed starting from 2001, with some additional positive observations beyond 2008 but only for the higher level of round-trip efficiency.

Table 4 – percentage of observations over threshold (baseload power)

		60%	70%
2001	rdm.base	0	0.01
2002	rdm.base	0.004	0.024
2003	rdm.base	0.004	0.036
2004	rdm.base	0	0.02
2005	rdm.base	0.004	0.012
2006	rdm.base	0.016	0.131
2007	rdm.base	0	0.032
2008	rdm.base	0.004	0.039
2009	rdm.base	0	0
2010	rdm.base	0	0
2011	rdm.base	0	0
2012	rdm.base	0	0

Legend: rdm.base: day-ahead to month-ahead (baseload price)

Table 5 – percentage of observations over threshold (peak power)

Year		60%	70%	Year		60%	70%
2001	rdb.wp	0	0.1	2007	rdb.wp	0.06	0.22
	rdb.mp	0	0.3		rdb.mp	0.22	0.41
2002	rdb.wp	0.1	0.2	2008	rdb.wp	0.03	0.1
	rdb.mp	0.1	0.3		rdb.mp	0.07	0.15
2003	rdb.wp	0.1	0.3	2009	rdb.wp	0	0
	rdb.mp	0.2	0.4		rdb.mp	0	0.03
2004	rdb.wp	0.1	0.2	2010	rdb.wp	0	0
	rdb.mp	0.1	0.3		rdb.mp	0	0
2005	rdb.wp	0	0.1	2011	rdb.wp	0	0
	rdb.mp	0	0.2		rdb.mp	0	0
2006	rdb.wp	0.1	0.2	2012	rdb.wp	0	0
	rdb.mp	0.2	0.4		rdb.mp	0	0

Legend: rdb.wp: day-ahead (baseload) to week-ahead (peak price), rdb.mp: day-ahead (baseload) to month-ahead (peak price).

The evidence from this preliminary analysis with a relative long time horizon seems to indicate that there are limited opportunities for financially viable arbitrage if looking at a period of a week or a month ahead of time, particularly if we consider the evidence from most recent years. Furthermore, under this scenario, energy storage facilities could be in competition with other forms of energy storage such has short and medium term gas storage facilities, whose investment costs have already been recouped, in most cases, and whose technology is more well-established.

We generate a separate time series for each of the maturities and we assess them for stationarity properties. Given that date matching among different maturities is crucial to be able to compare the seasonal pattern of assessments for different delivery dates (and for the computation of the park spreads) we had to restrict the time horizon considered in our statistical analysis of dynamic price patterns to those time periods when the dates for future deliveries matched the dates for day-ahead deliveries. In our data set complete daily availability and date matching is observed only from 3rd March 2005, which we have therefore selected as the initial date for the time series analysis of storage profitability.

Figure 3 illustrates the evolution over time of the ‘park spread’ measure calculated with respect to the day-ahead peak price for electricity over the period of time considered for our time series analysis:

Figure 3 Relative park spreads from base-load and peak day-ahead prices

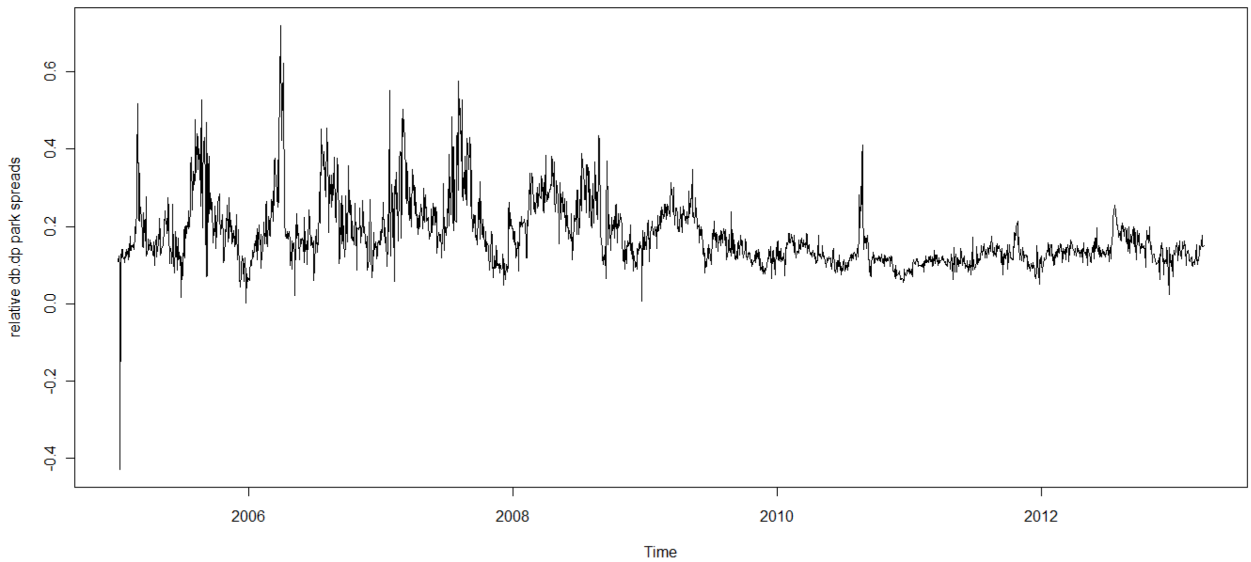


Table 3 contains the results of the stationarity tests for the 'park spread' measures:

Table 3: Stationarity tests (park spread measures - electricity)

	Day ahead baseload day ahead peak	Day ahead baseload Week ahead peak	Day ahead baseload Month ahead peak
KPSS test statistic	0.2633	0.2511	0.1663
Test critical values (1% level)	0.216	0.216	0.216
Phillips-Perron test statistic	-11.9789	-15.5477	-10.0073
Test critical values (1% level)	-3.968	-3.968	-3.968

Due to the fact that in most cases the results of the stationarity tests are conflicting we also carried out tests for fractional integration and in light of the lack of a clear diagnosis of stationary time series in the next phases of the work we apply first order differentiation, as a first approximation, in order to apply the same treatment to all series.

In the next stages of the analysis we model the dynamic pattern of the series using ARIMA-type models to establish the extent to which the past dynamic behaviour of the series can be used to forecast future behaviour. Then dummy regression models for weekly periodicity are also estimated. The results for the park spread measures in the electricity market are presented in Table 4:

Table 4: Seasonal ARIMA (1,0,0) model of park spread measures electricity (5-day periodicity)

	Day ahead baseload day ahead peak	Day ahead baseload Week ahead peak	Day ahead baseload Month ahead peak
SAR1 coefficient	0.6979 (***)	0.6040 (***)	0.7180 (***)
Intercept	8.3914 (***)	9.2110 (***)	10.7162 (***)
Adjusted R^2 (seasonal regression with dummies)	0.7497	0.6462	0.8155

Legend: (***) represents a significant coefficient at 1% level.

The same battery of stationarity tests were also carried out using information about gas prices to work out the arbitrage opportunities in the future gas market. Table 5 contains the results of the stationarity tests for the 'park spread' measures in the gas market:

Table 5: Stationarity tests (park spread measures - gas)

	Day ahead - Week ahead	Day ahead - Month ahead
KPSS test statistic	0.143	0.0398
Test critical values (1% level)	0.119	0.119
Phillips-Perron test statistic	-26.269	-12.635
Test critical values (1% level)	-3.968	-3.968

Finally Table 6 contains the stationarity tests for the clean spread measures, which consider the relative profitability of the gas and electricity markets:

Table 6: Stationarity tests (clean spark spread measures – 50%)

	Day ahead	Month ahead
KPSS test statistic	0.2214	0.1872
Test critical values (1% level)	0.119	0.119
Phillips-Perron test statistic	-7.387	-3.640
Test critical values (1% level)	-3.969	-3.969

Also for the case of the gas market we find conflicting results for the different stationarity tests and therefore also in this case we apply the first differences transformation to all the series before proceeding with the estimation of suitable seasonal ARIMA models to identify the patterns of dynamic behaviour of the future gas prices. Finally the same analysis is also applied to clean spark spreads which are computed comparing electricity and gas prices.

The results for the park spread measure in the gas market are presented in Table 7, while those for the clean spark spread are in Table 8:

Table 7: Seasonal ARIMA (1,0,0) model of park spread measures gas (5-day periodicity)

	Day ahead – week ahead	Day ahead - Month ahead
SAR1 coefficient	0.1587 (***)	0.5081 (***)
Intercept	0.4291 (***)	1.219 (***)
Adjusted R^2 (seasonal regression with dummies)	0.2796	0.7328

Legend: (***) represents a significant coefficient at 1% level.

Table 8: SARIMA (1,0,0) model of clean spark spread measures (5-day periodicity)

	Day ahead	Month ahead
SAR1 coefficient	0.8407 (***)	(AR1 coeff) 0.12 (***)
Intercept	11.410 (***)	10.58 (***)
Adjusted R^2 (seasonal regression with dummies)	0.8911	Not available

Legend: (***) represents a significant coefficient at 1% level.

It is important to point out that, based on the results presented in Table 8, it is apparent that the month-ahead clean spark measure does not follow the same dynamic pattern as the other time series. More precisely our regression results indicate that there is no identifiable seasonal pattern for this series which should therefore be modelled as an ARIMA (1,0,0) process.

Based on the results describe above, our analysis therefore moved to a shorter time horizon in order to evaluate the short term arbitrage opportunities, despite the fact that the adoption of such an arbitrage strategy would involve higher operational costs associated with charging and discharging the storage facility more frequently. This strategy would also generate competitive pressures from a wide range alternative storage technologies characterised by short term capacity (such as different types of batteries).

To illustrate the potential uses of the analysis of short term arbitrage opportunities, consider the example of the Park Spread based on buying base-load power day-ahead and selling day-ahead peak (assuming prices are unaffected by the storage facility itself). Once an initial buffer has been established, this set of backed contracts has the property that the efficiency of the system as a whole is better than the efficiency of the storage (because power purchased during the peak hours never enters the storage).

In an idealised case (without connection charges), if the round trip efficiency of the storage facility is, say, 80%, the efficiency of the contract is 90% because the energy delivered within the same day will remain in storage only for a short period of time and therefore the amount of energy lost through the storage process will be very limited. Thus a return of over 11% provides positive cash flow. Our initial analysis of day-ahead returns for electricity indicates that the returns averages at least 20%, although they have been declining in more recent years. This is a best-case scenario, but suggests strongly that there are conditions under which short term power storage is attractive to investors. Electricity prices have this property, whilst gas prices do not. This type of analysis with a shorter time horizon represents the next stage of investigation of arbitrage opportunities for storage facilities.

4. Forecasting future revenues: extreme value theory analysis

A further step in the analysis of the properties of the price distribution of the 'park spread' series involved looking at the distributional properties of the extreme values of the price distribution, as these are the observations that generate the most profitable arbitrage opportunities. The Extreme Value Theory (EVT) approach to the analysis of financial market behaviour is usually adopted in the financial econometrics literature for the purpose of evaluating the risk associated with trading in commodities that are subject to high volatility phenomena. This due to the fact that the EVT methodology allows the researcher to model distributions which are characterised by heavy tails. These features are indeed typical of the electricity market, where extreme observations emerge as a result of imbalances between supply and demand.

The identification of an appropriate distribution for extreme values requires the definition of a threshold beyond which the observed values can be classed as extreme. For the purpose of our analysis the thresholds for extreme values are exogenously determined by the chosen levels of round trip efficiency (60% and 70%, as discussed earlier). However, we find that in the case of round trip efficiency of 60% we have an insufficient number of observations for a reliable statistical analysis, while at the 70% threshold we can use 11.4% of the observations (335) from the original series.

Using 11.4% of observations from the original series we estimated a Generalized Pareto distribution, obtaining highly significant form and scale parameters. This estimated distribution satisfactorily fits the theoretical one, as illustrated by the density plot in Figure 4. The other 3 plots in figure 4, which contain the results of different diagnostic tests, also confirm the good fit between estimated and predicted values.

We also carried out the same analysis on the residuals from a seasonal ARIMA model with weekly periodicity, discussed in Section 3, in order to check for potential autocorrelation effects. In this case, as illustrated in the density plot in Figure 5, the fit between the empirical and the theoretical distribution is nearly perfect.

Fitting a heavy-tailed distribution to the data enables us to capture the irregular spikes which can be observed in energy prices series and should improve the predictive ability of our statistical models. Indeed this method can allow us to evaluate the probability of extreme events over a horizon of up to one year. The main purpose of this methodology in the financial econometrics literature is not to provide a forecasting tool, but rather to provide a measure of the risk associated with markets which are subject to high volatility. In the context of our analysis however extreme (positive) events represent an arbitrage opportunity rather than a risk for the future flow of revenue.

Our analysis therefore shows that the price dynamics observed in the UK electricity market has distributional properties that cannot be correctly modelled by adopting distributional forms that are commonly used for markets where imbalances between supply and demand are an unusual occurrence and therefore generate 'outliers' in the dynamic pattern. The market we are trying to model is characterised by extreme observations which results from demand and supply interactions and which need to be modelled using distributional forms which correctly represent the heavy tails typical of this rather unusual market behaviour.

Figure 4: Extreme value analysis (original series with70% r.t.e.)

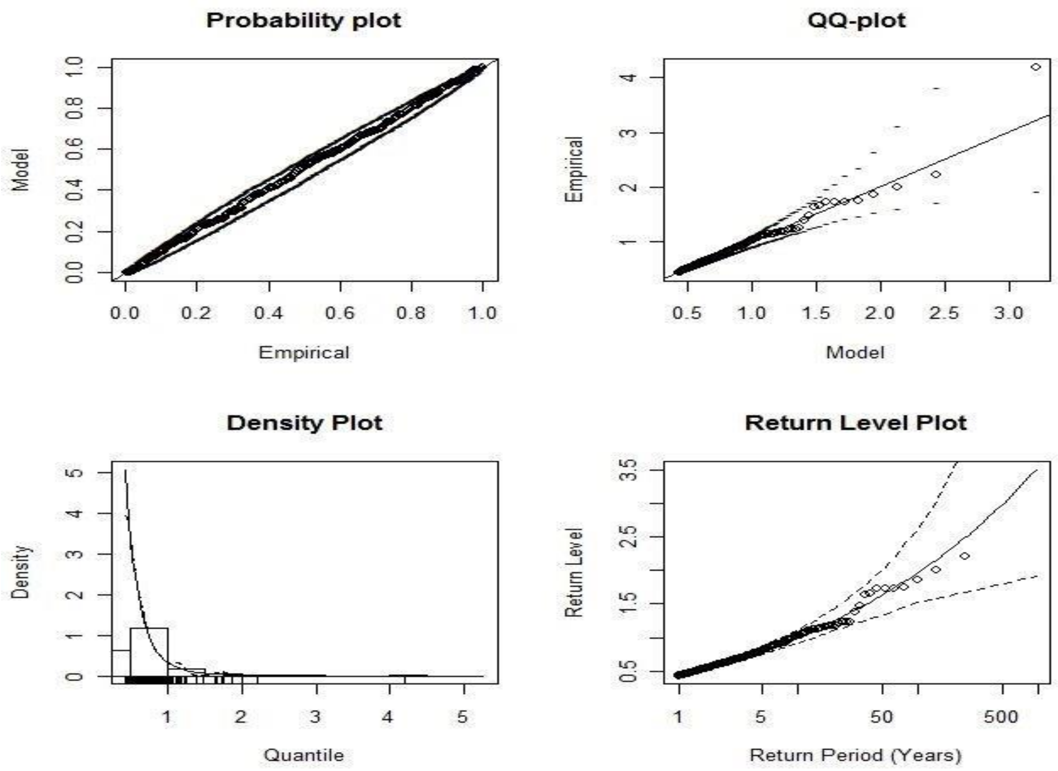
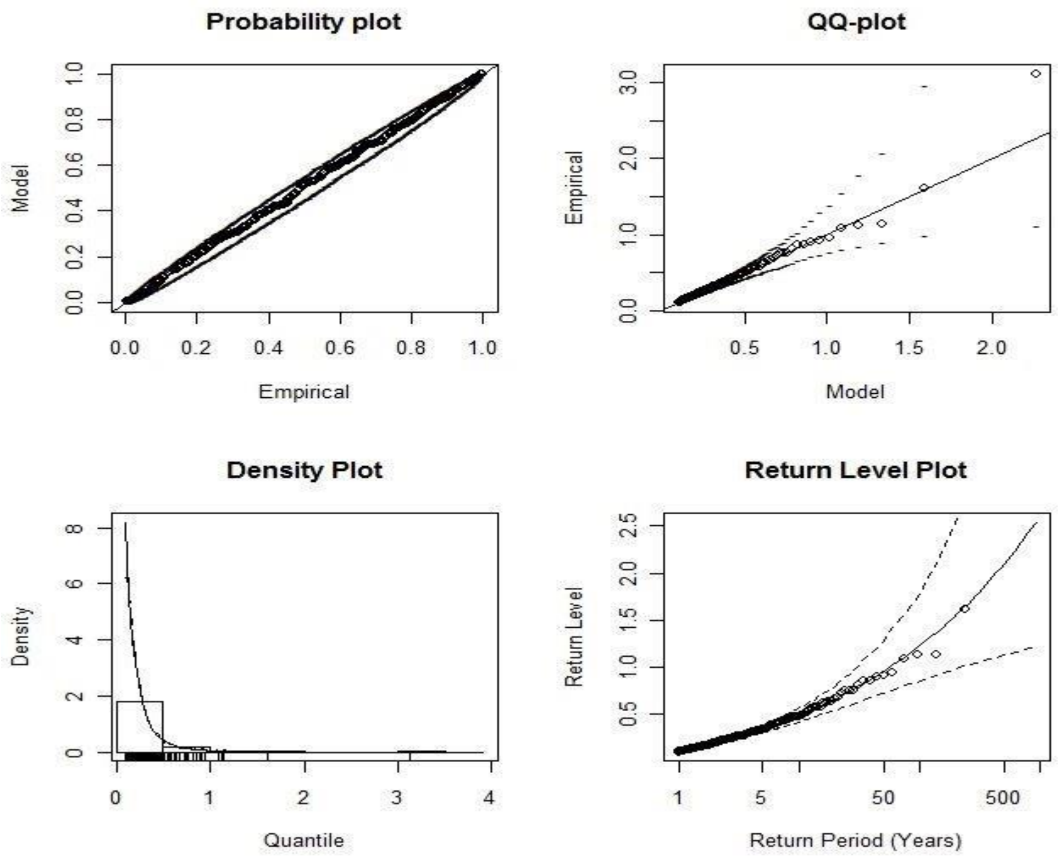


Figure 5: Extreme value analysis (residuals series with 70% round-trip efficiency)



5. Conclusions

The increasing deployment of intermittent generation, such as wind and solar power, in the electricity systems of several developed countries has made the technologies for energy storage more attractive despite the high set-up costs associated with these technologies.

This paper has investigated the potential financial viability of a risk-minimising strategy for operating a technology-neutral storage facility in order to exploit the arbitrage opportunities arising from price variations in the electricity wholesale market. Using assessments data for the electricity futures markets in the UK and relying on the ‘park spread’ measure of storage profitability we have produced empirical results which seem to indicate that the owner of a storage facility should be able to exploit arbitrage opportunities due the difference between base load and peak prices in the wholesale market, although these opportunities have become less prevalent in recent years.

The financial viability of the storage operations will be limited by the technological constraints imposed by the round-trip efficiency of the existing electricity storage technologies, so that the profitability of the storage facility, according to our initial results, will depend on the possibility that the charging and discharging of the facility takes place over a short term horizon, which would make it possible to exploit intra-day arbitrage opportunities. However, in order to assess the extent of these arbitrage opportunities, further investigation will be required, because as an initial graphical inspection of the time series properties of the park spread data indicates that the character of the series changes over the time period examined.

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