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Energy Sustainability

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Postal Address:
Chair in Energy Sustainability
Institut d'Economia de Barcelona
Facultat d'Economia i Empresa
Universitat de Barcelona
C/John M Keynes, 1-11
(08034) Barcelona, Spain
Tel.: + 34 93 403 46 46
ieb@ub.edu
http://www.ieb.ub.edu

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ANALYSING THE POTENTIAL ECONOMIC VALUE OF ENERGY STORAGE *

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ABSTRACT: This paper examines the likely market for electrical energy storage from a market viewpoint, taking market prices as given and determining the extent to which a strategy of arbitrage across the day, buying at the lowest price times at night and selling at the highest times during the early evening, generates profits in the British context. The paper sets out the potential problems as the market moves to absorb increasing amounts of wind, then characterises the nature of prices, which reveals the importance of a strategy in which power is absorbed into store for a relatively few hours of the day and discharged over a relatively few hours. The paper models the ongoing costs of operation and compares them with revenues, but does not consider construction costs. It argues that additional incentives may need to be put into place in order to render storage over relatively longer periods more attractive.

JEL Codes: L94, L98, H54, D24, Q41, Q47

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Lisa Flatley
University of Warwick
Coventry CV4 7AL, UK
E-mail: l.flatley@warwick.ac.uk

Monica Giulietti
Loughborough University
LE11 3TU, UK
E-mail: m.giulietti@lboro.ac.uk

Luigi Grossi
University of Verona
37129 Verona, Italy
E-mail: luigi.grossi@univr.it

Elisa Trujillo-Baute
University of Warwick and
Chair of Energy Sustainability,
Barcelona Institute of
Economics, Spain
Coventry CV4 7AL, UK
E-mail: elisatrujillo@ub.edu

Michael Waterson
University of Warwick
Coventry CV4 7AL, UK
E-mail: michael.waterson@warwick.ac.uk

* Monica Giulietti is a member of the panel of Technical Experts advising DECC on the delivery of the Electricity Market Reform but her contribution to this article is written only in her personal capacity, drawing solely on published material and her contributions to the academic research presented in the article.

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1. Introduction

Grid-scale electricity has two characteristics that distinguish it from every other good. Supply needs to equal demand at every point in time, to the second, or the system breaks down. Yet supply and demand naturally fluctuates over time. Storage takes place via the conversion from other forms of energy, for example via combustion, or conversion of electrical energy into other forms of energy, for example from chemical energy in batteries, or releasing potential energy in the case of previously pumped hydroelectricity. In traditional electricity systems, development over time from local supply to national and even international supply systems has required system interconnection, which takes advantage of less than perfect correlation in demand across space, alongside precise monitoring and operation of flexible generating plant. Most of the burden of storage across time has taken place at the input level, via storage of coal, natural gas and, to a lesser extent, fuel oil. This needs to change.

Why is this relevant, or important? The imperative to substitute renewable generating sources for fossil fuels in order to reduce carbon emissions has led to new and substantial challenges to the electrical systems of all countries. These are not widely appreciated by the green lobby, the public more generally, or economists.[1] Yet they are of vital importance to the maintenance of readily available electricity supply which is a cornerstone of economic activity as we know it. Most renewable resources, for example wind and solar power, are intermittent rather than firm and are not biddable in response to price. Enhanced interconnection provides a partial solution; other solutions involve demand management or storage. This paper examines the potential for commercially-operated storage to contribute, focusing on the case of Britain. Before doing this, we explain briefly why interconnection and demand management are insufficient in themselves to tackle the issue.

Solutions to these characteristics of electricity can take three basic forms. First, active demand management can be practised. Second, increased interconnection will facilitate

[1] This is partly because engineers (initially) and economists have been so successful in devising systems to deal with the problems, meaning blackouts are relatively rare. However we also know that, once a widespread blackout occurs, retrieving the system proves time-consuming and difficult.

transfer of power between countries according to relative price differences, enabling relative shortages to be tackled. Third, investment in energy storage can take place. The traditional method of storage is via pumped hydro facilities, but these require geological features that are not easily replicated. Thus, alternative approaches that are scalable involving compressed air, heat or battery storage have been raised as possible solutions. The main purpose of our paper is to examine whether there are sufficient economic incentives in place for such storage to be developed. Prior to that though, we engage in scoping the problem.

Interconnectors respond to spatial differences resulting from different existing generation facilities and different consumer habits across space.[2] By contrast, storage can respond to inter-temporal differences in loads resulting from habits across time (such as across hours of the day) which are substantial and, something of increasing importance, differences in renewable resource generation. Consumption is imperfectly correlated across countries, but there are many hours in the evening when the lights are on all over Western Europe, and many hours in the day in which all shops, offices and factories are operating. Demand management can make only limited inroads into this, in particular the rising evening demand as darkness falls. It is likely that both interconnection and storage will coexist as we move to a significantly less biddable system of generation, because solar power does not work in the evening in winter when demand is highest and wind power is inherently intermittent. Moreover, motivating a store to operate may be a more straightforward means of moving supply and demand into balance.

There are broadly two economic approaches that can be taken in evaluating the optimal level of storage in an electrical network (in particular in the context of significant intermittent generation). One is to evaluate the social benefits and costs of the storage, the other is to examine the private benefits and costs. The approach we take here is to focus on the private ongoing benefits and costs, on the assumption that storage will be operated commercially. In the longer-term, as conventional generation and distribution resources are retired or replaced, broader considerations come into play, but we do not

[2] A slight caveat: Interconnection with Norway allows storage across time, since advantage can be taken of the substantial pumped hydroelectric reserves available there.

discuss these here. (Barton and Thomson 2015)[3] Nevertheless, implicitly we are considering stores capable of holding hours' rather than minutes' worth of power.

We take an optimistic stance to examining the commercial benefits of storage. All we ask is whether the first commercially-operated store to enter the market, operating through arbitrage, more than meets its running costs, ignoring the costs of construction, which will be site and technology-specific and may qualify for subsidy. Because it is a first store, and by assumption is too small to influence prices, or generators, we take existing market prices as a good representation of what the store will face. In practice, the first store may be followed by others, stores may interact to reduce returns for other stores due to the effects on prices; generators may modify their strategies in response to the introduction of stores, etc. (See Hutchinson, 2015 ch2 and Cruise et al., 2015, for explorations of this issue). But if the first store cannot meet its running costs then such storage is infeasible as a commercial technology on the basis of arbitrage. There are other potential revenue streams, as we discuss later, but none clearly available for storage at present.

The questions we examine are (i) whether there is a clear requirement for storage, (ii) what will be the focus of commercially-provided storage and (iii) whether this focus appears sufficient to tackle the issues the system faces. Our plan in this paper is to explain the requirement through considering briefly the characteristics of wind power, the prime source of renewable energy in Britain. We explain why interconnection, as currently operated and planned, is a limited solution. We then move on to examining the characteristics of prices, which determine the nature of likely arbitrage activity, so in turn the likely characteristics of a store. Stores of different efficiencies and sizes are discussed. Finally, we move on to considering whether foreseeable future changes in the market will have an influence.

[3] An interesting and careful analysis that bears upon the social impact of storage is Gowrisankaran et al. (2015) on the social impact of solar power at various levels in the Tucson, Arizona district. However, this does not explicitly consider storage, including it ("perfect storage") only via the beneficial impact on smoothing output of solar power.

2. The requirement for storage

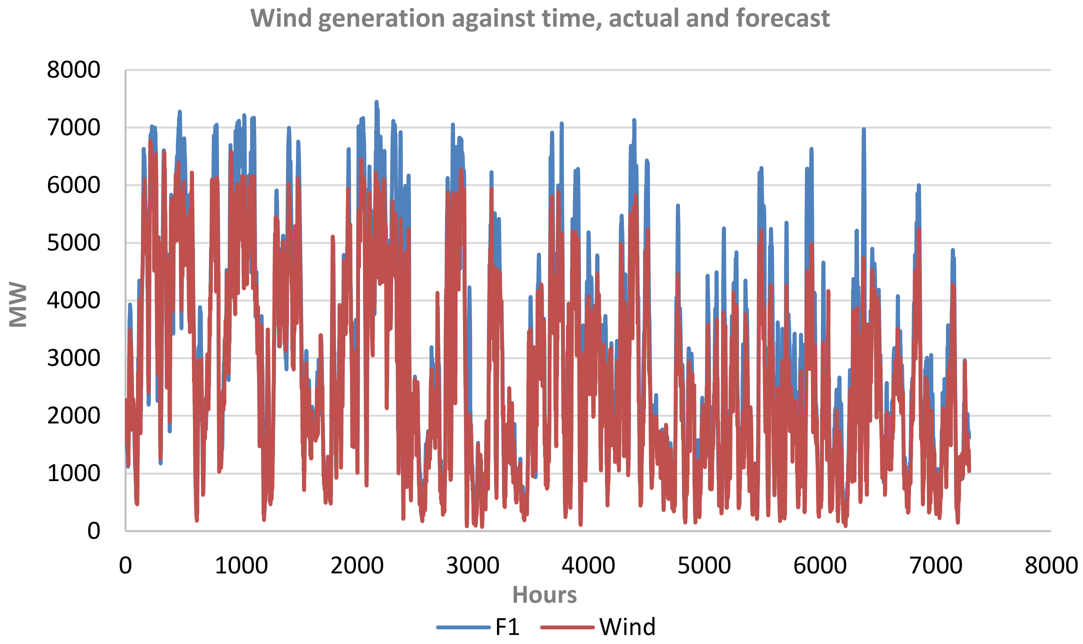
Storage is desirable if (a) there is significant variability in the source of power that requires some tailoring to conform to the desired profile of power demand and (b) alternative approaches are insufficient (or insufficiently competitive) to satisfy this tailoring requirement. We argue that both these conditions are satisfied in the case of Britain.

Wind power has important characteristics that provide challenges to modern electrical power systems. It is naturally unbiddable, it is extremely variable, its variability is time-correlated and it is difficult to forecast beyond a short period. Figure 1 below illustrates these features for Great Britain using a sample drawn from the ten months from end November 2014 to end-September 2015.[4] Mean generation is 2630MW, but its standard deviation is 1650. At times, virtually nothing is generated across the whole of Great Britain, at other times, almost 7GW or over 20% of average load is generated using wind, and on current plans this will increase significantly. There are periods within this sample when one or the other happens for hours at a time, for example for 18.9% of the time generation is below 1GW. Time correlation is not easily seen in the figure, but we observe 17 occasions on which wind generation is below 1GW for more than a day, including a few incidents when it is calm for more than two days. We also see that the day-ahead forecast, plotted in this graph, is of high accuracy, though it over-predicts somewhat. However, once we move beyond a couple of days ahead, predictions become extremely vague (the differences between actual and predicted values are very wide).[5] This leads to potential problems for long term storage.

[4] The constraint on length of time series arises because the very useful Gridwatch website only commenced capturing the day-ahead forecast in November 2014.

[5] This is an inference in the case of Britain; figures for Belgium, which also has a substantial proportion of its wind farms off-shore, suggest that predictions for five to seven days are rather uninformative. The problem is inherently difficult, since wind forecasts themselves are subject to increasing errors the further ahead they are made, and power generation is nonlinearly related to wind speed but is zero below or above critical speeds.

Figure 1: The characteristics of wind generation



There is substantial interconnection already between the electrical systems of continental European countries. This assists in smoothing net loads across countries, so that for example France, with its large and relatively inflexible nuclear fleet, can import electricity when domestic demand is highest and export when it is lowest. Most such interconnectors are limited in capacity, manifesting in continuing price differences across borders. Moreover, interconnection is of little use in smoothing correlated events across countries, such as when cold but calm winter days lead to little wind generation across the European continent. Demand management, for example through real-time pricing, has potential but naturally cannot tackle the problem that consumers want the lights on when it is dark, more than when the sun is shining and generating solar electricity. Demand management shades into storage, because storage can be implemented as either a response from users or an action taken by suppliers. On the part of users, immersion water heaters could (and some do already) heat water only when electricity is cheap, and those consumers with electrically-powered cars could charge up when electricity is cheap, and supply back to the grid when it is expensive. These incentives are similar to those involved in grid-scale storage, so although we focus on the latter, with some modification our analysis can take account of more consumer-based response in addition.[6]

Due to its island nature, Britain is less connected electrically with other countries than is typical for West European countries. Nevertheless, Britain has interconnection with France and the Netherlands (plus two with the island of Ireland), and further interconnectors are planned, the first two of which may come on-stream in 2019. These function as commercial operations on the basis of arbitrage on prices, due to differing marginal generation and load balances between Britain and its near-continent neighbours. That is, to the extent to which different influences play a part in determining prices within Britain and its connected countries, the interconnector will operate to move electricity from the lower-priced country to the higher-priced. Of course these interconnectors experience line losses and also conversion losses, since there is a double conversion from 3-phase AC to DC (to facilitate undersea HVDC cable transmission) and back again at the other end. However in total such losses amount probably to less than 10% of the power transmitted.[7] The total capacity of the French, Dutch, Norwegian and Belgian existing and planned interconnectors is around 6GW. Therefore, even if all are operating at full potential into Britain, they are only sufficient to tackle current wind fluctuations and are some long way short of being able to handle wind fluctuations once mean wind generation gets to around 20% of total power generated.[8]

Increased presence of wind (and PV) generation in the mix of electricity generation impacts on the system by increasing the variability of supply and reducing the store of energy. To put it another way, whereas coal as a generation fuel is easily storable, and gas is storable, wind energy is currently not stored. Whilst coal and gas generation are biddable (over different timescales) wind is not biddable; nor is solar power. Thus, as demand changes, coal and gas plant can be flexed to meet load, whereas wind and solar

[6] More significant modifications to the analysis are required to include the effect of electrical vehicle response.
[7] Entries in Wikipedia suggest losses from modern HVDC converters are approximately 2-3% at each end, whilst line losses are around 3.5% per 1000km. (Pages on HVDC converters and HVDC, accessed 15/12/15).
[8] Here we note that the island of Ireland, which already generates on average 20% of its power from wind, experiences very similar fluctuations to those exhibited in figure 1. Hence it is unlikely that the extent of fluctuation is reduced much as a result of a denser mesh of wind generators in Britain in future.

plant cannot, except through curtailment. And as these renewables take an increasing proportion of total load, these issues are exacerbated. Hence solutions are required.

At the same time, the storage requirements in a completely renewable system of operation are infeasibly large for commercial operation. This is well-illustrated through a recent paper (Esteban et al., 2012), although this is not the point the paper makes. It calculates the required magnitude of storage in a 100% renewable system in Japan (with solar at 31% of the total capacity) as 41TWh! Moreover, as is clear from figure 11 in Esteban et al.'s article, for much of the time this storage would be barely used; there is a long and almost continuous withdrawal from store in the period from July to September. Commercial stores of natural gas are able to operate on the basis of an annual withdrawal and charge cycle, but most of the variance in gas prices comes over the long term in an annual cycle, whereas in electricity it comes over extremely short intervals, commonly a day, as we show below. Thus there are two dramatic differences in storage as between gas and electricity, one being the nature of price movements over time, the other the physical space required for storage (Rough, a depleted gas field in the North Sea that comprises Britain's main store of natural gas coincidentally holds up to 40TWh of stored gas, which would amount to less than half that in terms of generated electrical power, but the energy content of compressed natural gas per cubic metre is much higher than in electricity storage media such as compressed air, so if used for compressed air storage it would not amount to anywhere near the equivalent amount of electricity).

3. Arbitrage as the focus of commercial storage

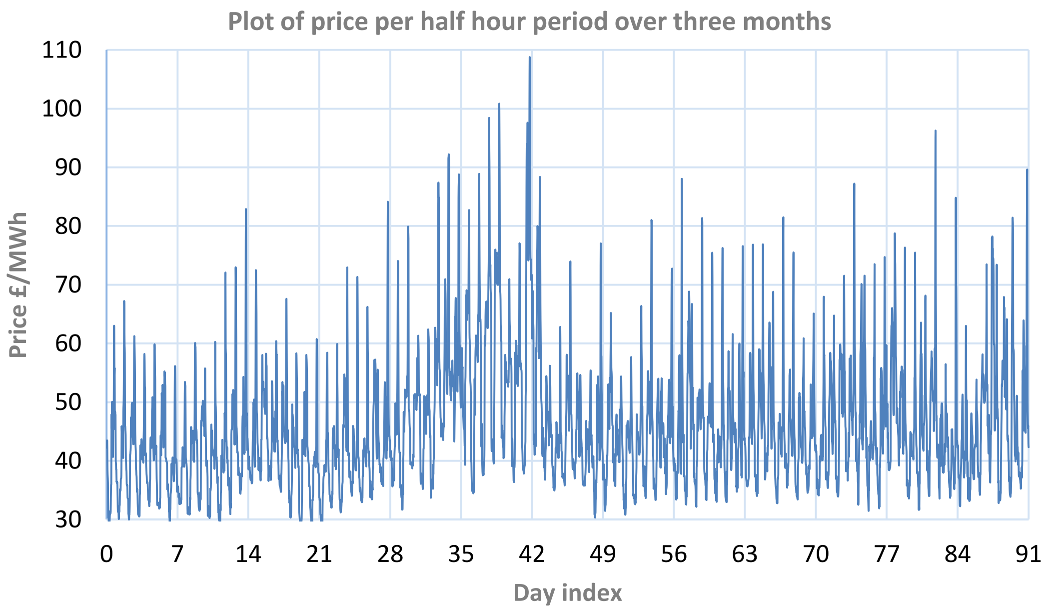
The classic focus for electricity storage, which is the one on which we concentrate here, is arbitrage. Existing hydro-electric stores make their money by buying power when it is cheap and selling it when it is expensive. Here we scope out the potential for additional storage by analysing existing pricing patterns. Subsequently, we will consider whether the incentives are likely to change in the foreseeable future.

One of the characteristic features of wholesale electricity prices is a consistent gap between prices during peak hours and prices in the middle of the night, arising because the marginal fuel technology for generating at peak has relatively high marginal cost.

This provides an opportunity for electricity storage to act as arbitrage between these periods. Of course, since storage is less than 100% efficient, the variation between periods needs to be large enough that it more than covers the losses engendered by storing. What scope is there for arbitrage earnings to encourage operation of storage? Here, we work with APX mid- prices obtained from Elexon over the three year period November 2011 to November 2014 to provide answers.

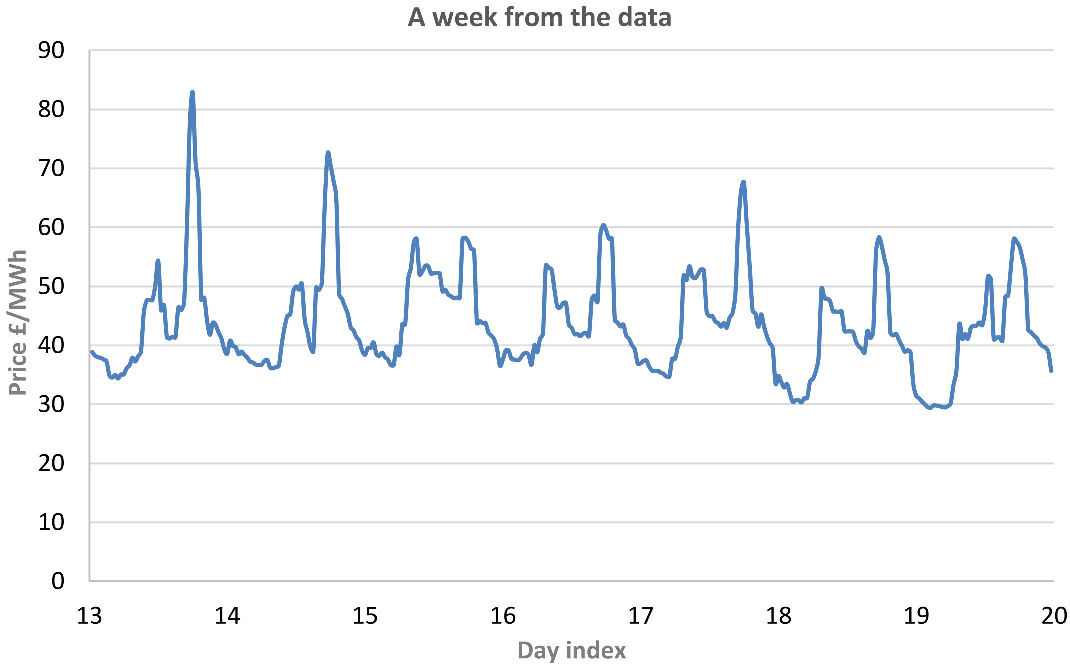
Figure 2a below illustrates the pattern of half-hourly market prices over the three month period from January to March 2014.[9] The graph shows two things clearly. First, wholesale prices fluctuate a good deal, from just under £30 per MWh to well above the highest retail price. Second, the underlying pattern is diurnal. This second point is demonstrated more clearly, together with a third more subtle point, in figure 2b, which takes a week (Monday to Sunday) from these data and examines it in more detail. Here we see that within each day, it is only a comparatively few hours for which the price is very high; this normally happens around 6pm in the evening. The effect is slightly lowered at the weekend. The lowest prices occur at dead of night, between around 2 and 4 am. Over our whole three-year sample, the average peak price is £51.26 per MWh, the average off-peak price is £40.94 per MWh. This influences the whole strategy that a store would need to follow.

Figure 2a: First three months of 2014



[9] We choose a three month period simply to facilitate graphical presentation of the features.

Figure 2b: Starts from 13 January 2014 (a Monday)



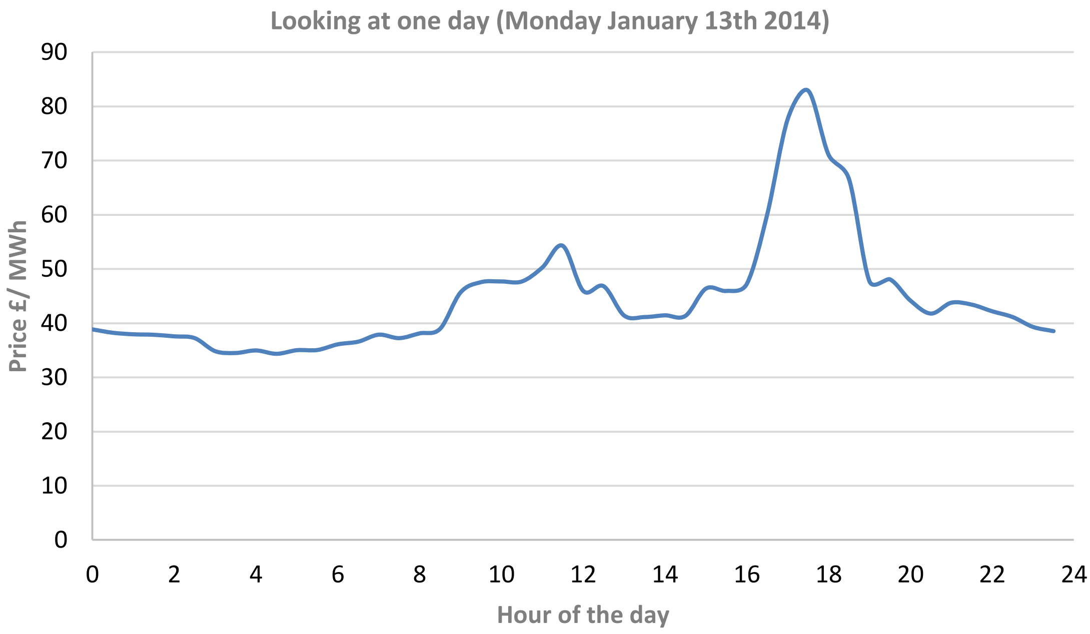
In order to make money simply buying off-peak and selling peak, a store would need to be at least 80% efficient. More generally, suppose the store's round-trip efficiency is θ. Then it is necessary for storage to be profitable that , where is the higher price at which the store sells and is the lower price at which the store buys, in both cases measured after the store has been in operation.[10] Its efficiency will influence the profitability of the selling prices that can be obtained compared to the prices at which input power can be purchased. Early experiments over a period of several years that we have performed involving general peak and off-peak prices reveal that the general strategy of buying off-peak (or baseload) and selling peak is unlikely to expose sufficient gaps in prices (the "park spread") for arbitrage to be feasible for a store which is say 70% efficient. There are occasions where the gap is large enough, but they seldom occur.

However, as can be seen for the example day in figure 2c (Monday 13th January, 2014), within the day there are certainly peak times when the price is over twice as much as it is in dead of night, so clearly there is potential for profitable diurnal arbitrage. Thus a

[10] In other words, the operation of the store will itself affect prices to some extent; these values are assumed measured after that effect.

more subtle purchase and sale strategy needs to be undertaken, in which particular periods showing the lowest prices and particular periods showing the highest prices, within the peak and off-peak periods, must be used. This leads in turn to two considerations. The first is the appropriate ratio of store size to pump size, which will itself be dependent upon the round trip efficiency. The second is development of a strategy that is able to look ahead in a relatively sophisticated manner to decide on when to take in and when to release energy from store. Flatley et al (2014) examine the nature of such an optimal strategy given the parameters of the store, focusing on the look-ahead time involved.

Figure 2c: An example of a fairly typical daily pattern (price)

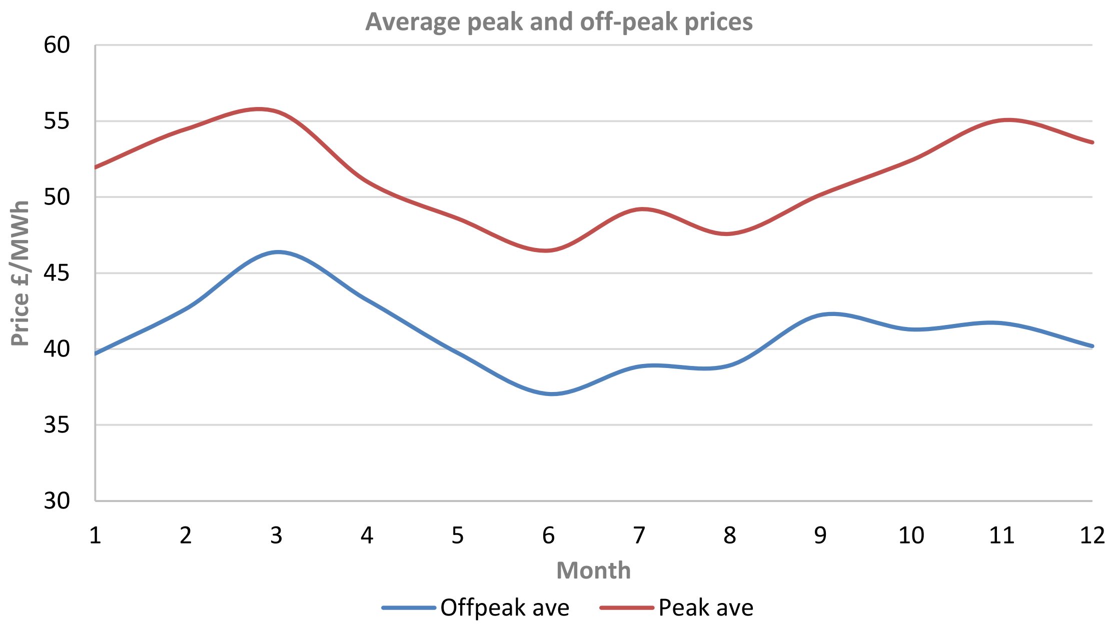


There is also a question of whether longer-term storage of energy from electricity is economically feasible, as it is in the case with natural gas. The answer in the British case is that it is not feasible, given likely store efficiency and current prices. Figure 2d shows that the inter-seasonal dispersion in prices is insufficiently large as to encourage longer-term storage.[11] The main feature is that electricity prices vary really rather little by month, so inter-month storage does not look to be profitable. Using these data, the ratio of the average off-peak price in June to the *peak* price in December is 0.69. This suggests long-term holdings are not commercially viable unless the plant is markedly

[11] Here we employ the whole of our sample of prices, of course.

more efficient than 70%, but this is beyond the capabilities of current storage technologies such as CAES and HTTP.

Figure 2d: Prices across all of our period of data, 2011 to 2014



Returning to consideration of diurnal storage, clearly it is inappropriate to have a store capable of carrying a large amount of energy if the purpose is to charge and discharge over relatively few periods. If the store has pumps capable of filling the store with a power rating of *P* MW, and the operator envisages the store filling over a maximum period of three hours (and discharging over no greater a period), then the size of the store need be no larger than *3P* MWh.

There are two main dimensions influencing the storage facility. The first is obviously the round-trip efficiency of the store, expressed as power that can be sold into the market divided by power taken from the market.[12] The second, less obvious, is the size of the store relative to the size of the maximum output.

However, the optimal size of store, given pump rating, is in fact endogenous, because it is influenced by the efficiency rating of the store. The more efficient the store, the longer is the range of time over which energy can profitably be discharged at peak (and

[12] Most of the remainder of the energy is likely to be dissipated as temperature changes in operation.

charged off-peak). Thus, given market prices, there are two determinants of the profitability of the store, efficiency and the number of periods of intake and output, and together these impact on optimal store size.

We have seen that there are only a few periods in which daily prices are at their peak. This limits the nature of storage which earns revenue through arbitrage. Moreover, there are only small sets of consecutive times for which prices are very high at peak compared with prices at off-peak.

We examine this in more detail by simulating the operation of a CAES (compressed air energy storage) plant in the market. Here, it is taken as given that the plant has been constructed, so the major part of the operating costs, the costs we take into account, are those involving charging and discharging the plant. The costs of pumping and turbining are given by Lund (2009) as 2.3€ per MWh and 2.7€ per MWh respectively. We translate these values into £/MWh at an exchange rate of 1.25€ per £. Energy input is assumed to be purchased (spot) at mid-market Elexon prices and sold also at these prices obtaining when sales take place. The plant operates for a number of periods filling (dependent on size of pump relative to capacity) and the same number of periods discharging later in the day or on the next day. For the purposes of this illustration, the strategy is “dumb”, that is the operation is assumed to be performed whether or not it is profitable. We simply take the total number of possible cases where a store can fill off-peak and discharge on-peak and examine what proportion of them is profitable, rather than adopting the approach of Flatley et al (2014).

Figure 3a assesses the outcome by looking at the fraction of transactions from off- peak to peak that give rise to profitable opportunities. It shows that if the plant is not particularly efficient, for example if it is 60% efficient, then the scope for profitable arbitrage is extremely limited- less than 10% of the off-peak fills give rise to profits. Once the plant is assumed more efficient, the proportion of transactions that is positive starts to increase quite strongly, so that the profit potential of storage is raised sharply.

Figure 3a: An example showing the fraction of positive transactions available for various efficiency levels over time

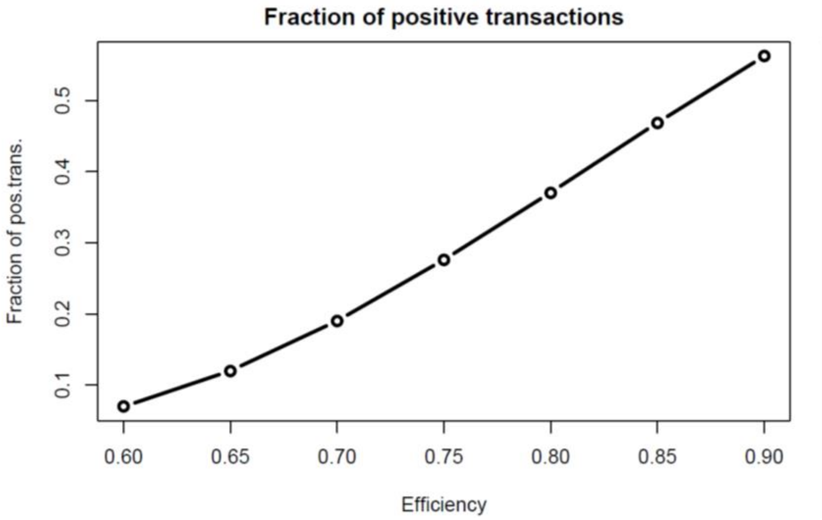
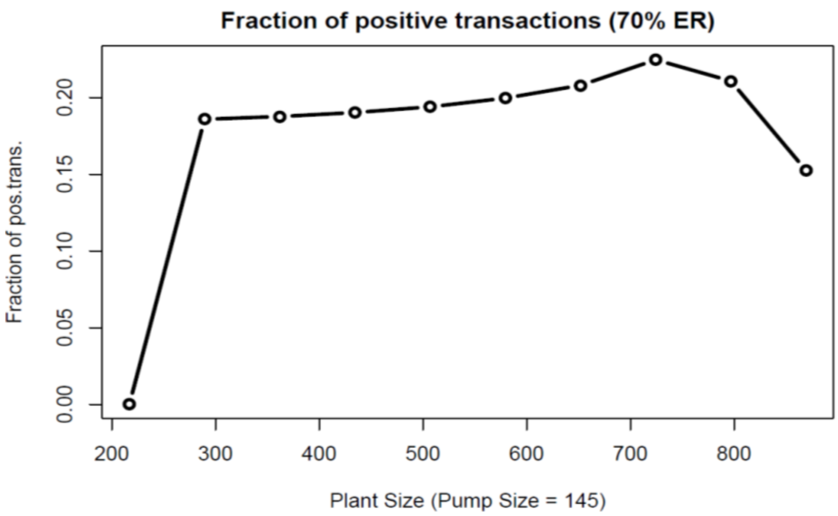


Figure 3b extends this analysis by considering relative sizes of plant size to pump size. For example, the plant may be large enough to store 6 hours' worth (12 half-hour periods worth) of energy, discharging over a similar period. Or it may be only large enough to store say 3 hours' worth. In each case, the question asked is both the fraction of transactions that are positive, and also the average profit to be earned from these transactions. Given the nature of the price patterns, it transpires that, for a 70% efficient plant, being capable of holding around 5 hours' worth of energy appears most desirable, although plants holding significantly less than this are not markedly worse. In fact, this size is not particularly sensitive to changing the efficiency from 70%, the operating size remains around 4.5 to 5 hours. Note that a store capable of inputting over 5 hours is still inputting for a period much shorter than the off-peak in total, which is a 12 hour period.

Figure 3b: This shows the fraction of positive transactions for various sizes of plant (implying various time lengths of fill) for a plant that is 70% efficient



The big unfinished question in this analysis is how to introduce uncertainty. A potential approach is to calibrate the model based upon the first two of the three years, and then operate a strategy over the next year as a test. The problem arises because of course not every day is going to be profitable, and an operator will not necessarily know in advance which days will be profitable and which not. This strategy might be based upon choosing particular hours (for input and output) based upon the first two years and then operating those same hours in the third year, regardless. Alternatively, it could be based on purchasing when prices go below a certain level and selling the next time they go above a particular selling level, at the start of (say) a four-period output. That is, there would be key action prices. We leave further experimentation on this point to a later paper.

4. Foreseeable changes in the price structure

So far we have examined the possibilities for arbitrage under a number of limiting assumptions. We have assumed that the average gap between low and high prices is likely to remain constant into the future, although there are forces that will push this in both directions. Therefore we should consider the nature of these forces to some extent.[13]

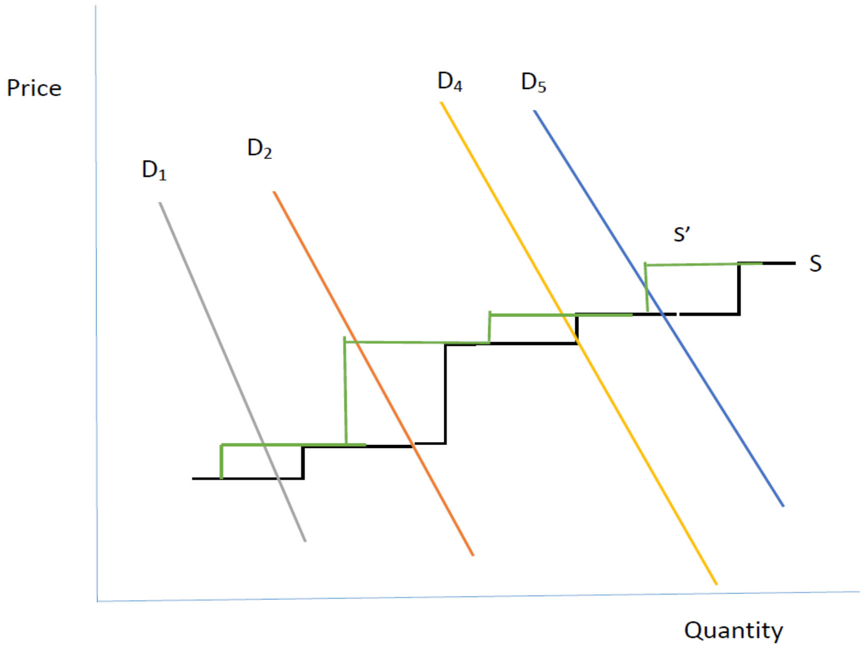
For example, increased use of “smart” technologies within the home and business may smooth power demand over the day relative to the situation at present, lowering margins between peak and off-peak prices. On the other hand, the German experience (Grossi et al, 2014) illustrates that a key factor relates to what is assumed about plant that is retired, once renewables become more important. If inefficient peaking plant is retired, the gap could grow, whereas if substantial baseload plant is retired, the gap may again narrow. But the answer actually depends quite subtly on the nature of the existing plant’s marginal costs relative to the marginal costs of the plant that is retained and it

[13] We maintain the assumption that the store is too small itself to influence prices significantly, although we are not specific on the size of the store. To put this point slightly differently, we assume there is sufficient capacity that can be purchased in the night-time period without causing an increase in prices, and (a lesser problem) the market is willing to take power in peak periods without the additional supply lowering prices measurably.

is not possible to give a general answer on this point. The benefits of arbitrage may either increase or decrease over time.

Figure 4 illustrates the ideas. Suppose initially that demand ranges between D_1 and D_2 off-peak, and D_4 and D_5 on-peak. If some plant at the lowest end of the merit order or supply curve S is retired (say, nuclear powered and coal powered plant), then the supply curve shifts to S', the green line. Both ranges have increased, but the lower range has increased more and the mean value of off-peak price has increased. However, this is due to the big jump in marginal cost (and so price) at the lower end of the merit order. The opposite effect could as easily happen if there is a big jump in the distribution towards the upper end of the merit order.

Figure 4: Illustrative movements in the merit order and their effect on average peak and off-peak prices



A more far-reaching consideration is whether prices will come to reflect the influence of wind more significantly over time, so that prices are substantially higher when conditions are predicted to be calm. To examine this question, we investigate the current extent to which wind forecasts influence price and also note briefly the extent to which prices are influenced by forecasts in Ireland, where wind penetration is much deeper than in Britain.

Wind generation forecasts in Britain are only published for the next day and the following day (actually, 36 hours ahead) by National Grid. Since late 2014, these forecasts have been archived by the "Gridwatch" website. The exploration here focuses on data forecasting over the period from end-November 2014 to end- September 2015, making use of these data.[14]

We wish to predict price based upon load and wind generation, in order to examine whether there is a predictable pattern. The implicit assumption is that, apart from wind, other generation is essentially controllable and will involve a portfolio combination of gas and coal generation varied according to relative factor price movements. Wind, on the other hand is not controllable, but may be forecast. Of course, load is potentially endogenous, because load and price may be viewed as being jointly determined by demand and supply factors. Hence we instrument for load in examining the impact of wind forecasts and load on price. More formally, our model is as follows:

$$p^f_{t+1,t} = g(L^f_{t+1,t}, W^f_{t+1,t})$$

where the meaning of $x^f_{t+1,t}$ is the forecast at t of the value in $t+1$, p is price, L is load and W is wind generation. A similar model could be used for longer-term forecasts, though see below. Load is instrumented for these purposes by a deterministic polynomial model of the day and time of day. Wind generation forecasts come from the Gridwatch site and price is the APX day-ahead forward mid-price for that half hour (or, alternatively, and with very similar results, the weighted average for the half hour, a two-period block and a four-period block styled Reference Price Data by APX). The IV regression is shown in table 1 below. Both variables are very significant.

[14] The Gridwatch data are very much "as is". Substantial cleaning is required in order to render them suitable for analysis. The reports on which we base our analysis are hourly on the half hour, where gaps in reporting have been smoothed. We concentrate on forecasts of wind and ignore solar power, because currently this appears not to be measured as an output at grid scale in Britain, rather it feeds into the distribution network and impacts negatively on load.

Table 1: Regression of forward price on predicted load and forecast wind

IV regression of forward price (p) on forward load and forecast wind

	Coefficient	st error
Load	$7.41*10^{-4}$	$1.87*10^{-5}$
Wind	$-1.45*10^{-3}$	$-5.92*10^{-5}$

Notes:
7290 observations. Rsq 0.304
Instruments for Load are day, time, squares and cubes of these, interactions between these.
The Rsq for the first stage is 0.735
We are able strongly to reject the presence of a unit root in Price, using the Augmented Dickey Fuller test with up to 25 lags. Similarly, we are able to reject a unit root in Wind.
The Sargan test of the exclusion restriction is also comfortably passed.

Based upon this regression, we find that the elasticity of price with respect to load, at the mean, is around 0.6. The elasticity of price with respect to the wind forecast is just over 0.1. To interpret this, note that a 1 standard deviation change in the forecast for wind, at the mean, would result in a change in price of £1.63, where the average price is just over £40 per MWh.

Interpreting this figure in the context of our question, near-term wind forecasts clearly do have an impact on price which is measureable. At the same time, a significant calm period does not change price by enough to make it worthwhile to store for longer than a day, at current values. This is because the diurnal variation in price dwarfs the impact of wind on price.

This leaves open the question of the impact of greater wind penetration and possible longer-term forecasts. However, similar experiments on price based upon day-ahead forecasts for Ireland, where wind is at 20%, suggest only a modest impact on price.[15] The 36 hour forecast reported via Gridwatch has a similar, although somewhat lesser, impact on price. But what of longer-term forecasts that might predict calm or a windy period for several days?

[15] Less formal estimates for Ireland suggest that a one standard deviation upwards (downwards) in the wind forecast, at the mean, creates a little less than a 7% shift downwards (upwards) in the day-ahead price. This is on the basis of a three month period in winter 2014/15, but without correcting for potential endogeneity of load and using the EA1 (first ex ante) run of prices.

Here, there is a potential problem from the viewpoint of capturing market-relevant information to engage companies to store for several days rather than holding diurnally. Longer-term forecasts for Britain appear not to be published, but the Belgian system operator publishes forecasts for up to a week ahead. Simple calculations we have performed suggest that these are rather inaccurate beyond around three days out. Similarly, a Spanish commercial website (Meteologica) produces forecasts for example for German regions, but again beyond a few days, the the difference between actual and predicted values on these are extremely wide. At present levels of wind penetration relative to flexible biddable plant, a day's notice is enough for planning purposes. However, it remains possible that if wind penetration should increase significantly, or biddable flexible plant becomes short, a commercial imperative to develop better long term wind forecasts may arise.

5. Concluding remarks

Are things likely to change much in future? The characteristics of wind imply that whilst on average it can generate significant amounts of electricity in countries such as Britain, there is a very substantial variance around the amount produced. Moreover, there is a time correlation in generation that means periods of calm tend to occur together, as do periods which are exceptionally favourable to wind generation (not the most windy days, when generation has to be curtailed, but days with significant wind). If the electricity generation system relies to a significant extent on wind, it needs to find methods of covering the periods when wind is not generating. In particular, periods longer than a few hours are ill-suited to demand management tactics, because switching a refrigerator or immersion heater off for several days, or refraining from charging your electric car, are unlikely to be practical propositions. Nor, to the extent that wind generation may be low across the European continent for several days under certain climate conditions experienced in winter, does interconnection provide a good solution. This type of operation, holding power over several days, would not appear profitable on the basis of present price patterns within storage facilities given current and projected efficiency rates and might be better addressed by gas plant constructed for the purpose, for example.

Two alternatives suggest themselves. The first is that pricing patterns will change sufficiently to make it worthwhile to store for longer periods on an arbitrage basis. The second is that new means of incentivising longer term storage may need to be contemplated as an alternative to “diesel farms”. The obvious solution here is for storage to enter the capacity market,[16] since storage in media such as CAES is technically feasible for periods in excess of a week, and arguably also socially feasible according to calculations by Barton and Thomson (2015). At present the incentives to encourage this appear not to be present, but they may emerge in future.

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[16] At the distribution level, small-scale storage, for example in batteries, can also improve quality of power provision.

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