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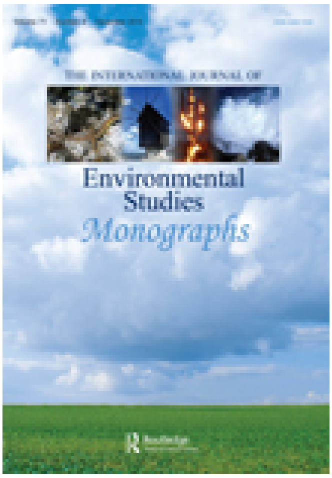

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Can negative electricity prices encourage inefficient electrical energy storage devices?

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This paper explores whether negative electricity prices can change the rationale that efficient energy storage devices are more economical for arbitrage in electricity markets. An established model algorithm to determine the maximum available arbitrage revenue and optimum schedule of electrical energy storage (EES) operation is used to simulate storage with a time-series of electricity prices which includes some negative prices. Our results suggest that at any likely frequency of negative electricity prices, inefficient EES is not encouraged, and can only be encouraged for EES devices with very low energy capacity to power ratios.

Keywords: Energy storage; Negative electricity prices

1. Introduction

There has been a growing interest in negative spot prices for wholesale electrical energy and the impact they may have in providing additional revenue for electrical energy storage (EES) operators.

One revenue stream for EES is from energy arbitrage; buying and charging a storage device at times of low-cost electricity and discharging and selling it at a later time period at a higher price. All energy storage devices suffer some sort of energy penalty (round-trip efficiency loss), which is dependent on both the technology and manner of operation. EES can profitably use these price differentials if the cost of operation (including the cost of the electricity used in charging) is less than the selling price by a given percentage. The price uplift must cover the round-trip efficiency losses, as well as operation, maintenance and investment costs of the energy storage device. Several researchers have examined the ability of storage to derive revenue via arbitrage [1–3] and conclude that high round-trip storage efficiencies are essential in making any storage device economically attractive. No researchers previously have considered the effect of negative electricity prices. This paper considers whether the rationale to have energy storage devices with higher round-trip efficiencies is valid when subject to negative electricity prices.

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1.1. What are negative electricity prices?

In recent years, several wholesale electricity markets have exhibited the use of negative electricity prices; when generators pay to have their electricity consumed, whereas in normal market conditions of positive prices, generators are paid for their electricity. For example, in the German day-ahead market in 2013, there were negative prices in 48 h, zero prices in 23 h and the price was below 10 €/MWh in 326 h, whereas in the German intraday market, there were negative prices in 79 h, zero prices in 2 h and the price was below 10 €/MWh in 355 h. In each case, these values are out of a total of 8760 h [4]. Clearly, negative prices occur in both the intraday and the day-ahead market, and a storage operator able to trade in either of these markets could seek to take advantage of these opportune prices.

The trading of wholesale electricity through power exchanges is meant to provide a transparent method to 'discover' market reference prices for electricity. Typically, the power exchanges match willing buyers and sellers of electrical energy using predefined blocks or electrical energy or 'products'. The reference prices are then calculated by the power exchanges with agreed formulae that typically weight qualifying trades of electricity [5]. In many liberalised electrical energy markets, these reference prices are used to influence other trades of electrical energy that do not take place through the power exchanges, e.g. bilateral trades. It is thought, therefore, that the reference prices are an important basis for the entire electrical market, not just the trades that take place through the power exchanges. In Great Britain (GB), these weightings and the criteria for qualifying trades are formalised and can be changed by the Imbalance and Settlement Group [6] to reflect changing market conditions or desired outcomes from the reference price.

Different market structures provide different means of discovery of a market price for electrical energy, with a pool structure still being common in the USA. There used to be a pool structure in GB for its electrical energy market. All trades of electrical energy happened through the pool, and were based on a merit order to match the forecast demand with the bids that generators had provided. This was effectively a day-ahead market with the system operator accepting or rejecting bids in order to match supply and demand. All generators were paid the same price for their electricity, regardless of their bid price, which was set by the most expensive bid that was accepted. This all changed when GB introduced a different market structure, the 'New Electricity Trading Agreements' in 2001. Newbery and Green have comprehensively described the different market structures [7–9].

In practical terms, a higher price should encourage the generation of electricity from additional higher marginal price plant, whereas a lower price should discourage generators with higher marginal costs from being active in the market at that time. Negative electricity prices represent particular times where the market conditions suggest an oversupply of electricity relative to the forecast demand. The intraday or day-ahead wholesale market is expecting a position of oversupply, and can be viewed as a strong signal for either demand to increase, or for generation to decrease, or both.

Typically, there are also separate markets from the pool or the power exchange markets to allow the system operator to undertake balancing actions in close to real time, and in GB, this is known as the balancing market [10]. The system operator has overall control over this real-time window, and can accept bids or offers from generation or indeed suppliers to add or reduce their generation or demand. This is separate from and crucially different to the day-ahead or intraday power exchange markets for wholesale electricity, as the only counterparty to any trade in the real-time period is the system operator. Trades are therefore forbidden between other parties in real time and although storage can also profit from this balancing market, it is not discussed here.

1.2. How do negative spot prices arise?

Several European countries now allow negative electricity prices to occur in their electricity markets: Germany/Austria, France, Austria, Switzerland, Belgium and the Nordpool markets. In GB, negative electricity prices are not supported in the intraday market, but are allowed on the day-ahead market (By September 2014, this development had not yet occurred.) Because the lowest price limit for participants in the GB intraday market is zero, negative prices cannot occur as market participants cannot enter a potential trade with a value below zero. This lower limit is, however, being investigated, and may well change to harmonise with the day-ahead market, where the lower limit is minus £400 (a negative price of £400). If this happens, the GB intraday spot market price would then have the potential to become negative.

Two mechanisms can give rise to a power exchange and a market structure for accommodating negative spot prices.

The first mechanism occurs when an inflexible electricity generation mix coincides with a low demand, giving rise to a potential oversupply. This can be caused when generators decide that the cost associated with shutting down and restarting of their generation plant is greater than the cost of paying an external party to take the generated electricity for a limited period. Clearly, this is not a financially stable business strategy for longer periods. This can happen when a thermal generator wishes to maintain a minimal stable generation for a time to avoid a slow and expensive shut-down-and-restart cycle. This avoided shutdown could keep the plant ready to participate in another more profitable market at a later time (e.g. the balancing market), or make the plant available at peak price times of day. Overall, the generator is prepared to accept negative prices (to pay) over a limited period in order to receive greater revenue (to be paid) at a later time: the net revenue is positive.

The second mechanism results from subsidies a generator may collect from the generation of electricity; e.g. a feed-in-tariff to support renewable generation. In this case, a generator (e.g. of wind power) could reduce its sale price to become negative, in the knowledge that it will receive a subsidy of a greater value to cover the negative price on a unit basis. The generator would still receive a net positive payment for the electricity it generates when the traded negative wholesale price and the subsidy are aggregated. As an example, the German feed-in-tariff subsidy for onshore wind is about €89/MWh [11]; even if the wind generator bid into the market at -€10/MWh the net unit price it would receive would be €79/MWh. The overall nature of this mechanism is similar to the first one: the net benefit to the generator is positive, even though there may be a negative wholesale price.

Negative electricity prices mean that generators will pay other parties to take the electricity that they generate. Although negative electricity prices could occur in the first instance without renewable generation, renewables – a source of variable generation – significantly add to the likelihood of such prices. Genoese *et al.* [12] studied negative electricity prices on the German day-ahead spot market and found that of the global variables that characterise the market, wind had the highest correlation with negative electricity prices.

There are several economic arguments for the accommodation of negative electricity prices, such as reducing the reward for *wrong-time* renewable energy; essentially causing them to pay back some of the subsidy as a result of their inflexibility. Another reason is to allow for better market coupling between other European markets that do support negative prices. An alternative view, however, is that negative spot prices indicate that a subsidy regime is distorting the wholesale electricity market and this should be seen as harmful [13]. This view has much to do with analysis of a pool-based market and the assumption that wind generation is crowding out conventional thermal plant.

The mechanisms that can lead to negative wholesale electricity price in the spot market are a very different phenomenon from generators being paid to shut off generation to balance the network. In GB, the balancing market is a wholly separate market that is driven by real-time transmission network constraints as well as locational balancing between actual generation and actual demand (as opposed to notified generation and forecast demand). One contentious issue in the UK is that for wind generators these balancing market payments *usually* result in significantly higher payments per MWh than the subsidy itself is worth [14]. Wind farm operators claim this is due to costs associated with switching the turbines off and on as well as additional wear and tear, although so far no breakdown of wind curtailment costs is in the public domain.

1.3. Negative electricity prices and energy storage

Negative prices can have a profound consequence for energy storage; instead of purchasing electricity to sell back to the market at a later time, storage is *paid* to take electricity that is sold back to the market at a later period. Accordingly, if there are no fixed storage operational costs, it is *always* beneficial for storage to charge using this negatively priced electricity, irrespective of the positive selling price. That negative electricity prices should encourage the participation of energy storage in the electricity market is often observed. This is not surprising because negative prices represent a lack of flexibility in the electricity network, and EES adds flexibility. Yet, there may be a risk in relying on negative prices to encourage energy storage, as they have the potential to reward inefficient energy storage devices more than the most efficient ones.

1.4. The methods through which negative electricity prices can encourage inefficiency

It seems bizarre that a less-efficient energy storage device could generate higher revenues than a more-efficient device, but this is possible when negative electricity prices occur. This is because an inefficient storage device requires more electricity to charge fully, and so the presence of negative electricity prices introduces the possibility that an inefficient storage device will produce a greater amount for its operator than a more-efficient storage device of the same scale and charging rate. This difference in income when charging can be sufficiently large that the equivalent but more-efficient device may not be able to compensate this financial differential when discharging. This is often misinterpreted to conclude that negative electricity prices always encourage inefficient EES. But this situation can only arise if the capacity of the devices is small enough that the more-efficient device becomes fully charged before the end of the duration of negative prices. If this is not the case, then the more-efficient device will always be able to derive a greater revenue, as both devices will receive the same income from charging (as their rates of charging are the same) and the more-efficient device will receive a larger income from energy discharge.

If the period during which negative electricity prices occur is sustained long enough, however, so that the efficient energy storage device becomes fully charged whilst the negative price period is still available, then it is possible for an inefficient device to generate a larger revenue. For example, consider a storage device with a capacity of 2 MWh and a rated charge and discharge power of 1 MW. If there are more than two hours with negative prices, then a less-efficient device may produce a greater revenue. This is because a less-efficient device can exploit more consecutive periods of negative electricity prices, whereas the 100% efficient device can only exploit two consecutive negative electricity price periods before it becomes fully charged. This is illustrated in figure 1, comparing a 100% efficient and a 50% efficient device. Positive denotes buying (charging – adding energy to the store) and negative denotes selling (discharging energy from the store).

Figure 1(a) and (b) show the energy bought and energy sold per period for the 100 and 50% efficient storage devices, respectively. Figure 1(c) and (d) show the quantity of energy stored at the end of each period. It is assumed that with a round-trip efficiency of 50% the charging process and the discharging process each have an equal efficiency of 70.71%. Therefore, only 70.71% of the energy bought is stored, and only 70.71% of the energy removed from the store can be sold. It can be seen that because of these losses the 50%

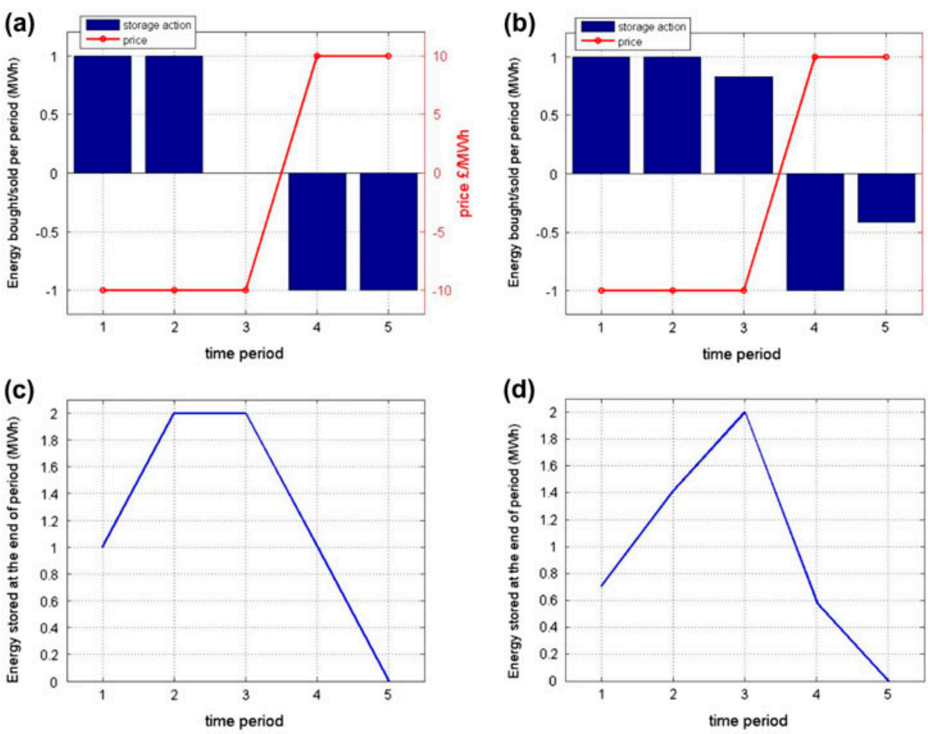

Figure 1. (a) Charging and discharging schedule for 1 MW 2 MWh 100% round-trip efficiency storage device. (b) Charging and discharging schedule for 1 MW 2MWh 50% round-trip efficiency storage device. (c) Energy stored corresponding to figure 1(a). (d) Energy stored corresponding to figure 1(b).

efficient device can exploit a larger proportion of the negative prices. Therefore, although it discharges less electricity at positive prices, it generates a higher overall revenue.

The situation becomes ever more bizarre if storage is allowed to charge and discharge at negative prices. Consider two successive periods with the same negative electricity price. One way for any energy storage device that is not 100% efficient to generate revenue could be to charge at the first period and discharge at the second period. Thus, the storage would be rewarded for the charging, and penalised for the discharging; but because of the round trip losses the quantity of energy discharged would be less than that used to charge. In result, even if the price of electricity remained unchanged (at its negative value) the revenue gained by charging at the first period would outweigh the revenue lost for discharging at the second period. Hence, if storage operators exploited this method of revenue generation, it would actively encourage inefficiency.

This is obviously undesirable and policy would no doubt require removal of this perverse incentive, by imposing further penalties on energy storage devices that choose to discharge at negative price periods.

The second method of storage devices choosing to discharge with negative electricity prices is likely to represent a very extreme case. It is more informative to look at the case in which storage can charge at negative electricity prices but will discharge at high positive electricity prices. Accordingly, we use a model algorithm that calculates the maximum possible revenue available to energy storage devices through arbitrage, which buys low-price electricity and sells it at times of higher prices that are positive. Hence, the model will not generate revenue from the second mechanism of both buying and selling at negative price periods. The chosen arbitrage model has been adapted from the paper by Connelly *et al.* [15]. The model is written in MATLAB and the code can be downloaded [16].

2. Simulations of energy storage and negative electricity prices

Given a time-series of electricity prices, charging and discharging limits, a round-trip efficiency and some maximum storage capacity, the algorithm returns the schedule of operation of the storage device that delivers the maximum revenue, along with the maximum revenue value. Connelly *et al.* [15] provide a detailed description of the model algorithm used in the simulations; and for completeness, a brief description is given here:

(1) The model algorithm identifies the maximum price in the time-series and marks it as MAXhour.
(2) A range around MAXhour is then identified in which it is physically possible for the storage device to charge. If the range is empty or only constitutes MAXhour itself, then MAXhour is removed from the time-series. It is possible for the charging period to occur after the discharging period only if there is sufficient energy stored at all the times between the discharge and the charge period so that the minimum energy within this period is greater than zero.
(3) The minimum price hour within this range is identified (denoted MINhour) and the cost of charging at this hour and discharging at MAXhour is calculated. If this action generates a net positive revenue – i.e. if the cost of charging at MINhour is less than the revenue derived from discharging the stored energy at MAXhour – then this action is implemented in the storage devices schedule, provided that it does not violate any charging power, discharging power or energy capacity

constraints. The value of these constraints is called the 'Storage bottlenecks'. Equation (1) summarises the revenue condition:

$$\text{price (MINhour)} < \eta_{rt} \times \text{price (MAXhour)} \quad (1)$$

η_{rt} is the round-trip storage efficiency. If there is no revenue incentive, then MINhour and MAXhour are removed from the time-series.

(4) The algorithm then checks whether the storage operation has reached capacity at either MAXhour or MINhour and if true removes these hours from the price time-series.

(5) This process is repeated until all the hours have been removed from the price time-series.

Simulation results are presented for a typical single day's worth of electricity prices and for a year of electricity prices. The price used is the UK 2013 Market Index price, or the 'spot market' price, which is modified to include several hours with negative electricity prices. Figure 2 shows a flow chart depicting the operation of the energy storage arbitrage model. It is assumed that the storage device is a 'price taker' and thus, its operation does not influence the price of electricity. This is a reasonable assumption given the current push to develop small–medium-scale EES devices and encourage their participation in liberalised electricity markets. Of course, with a large enough capacity of EES this assumption will be invalid.

It should be stressed that the simulations in this paper serve mainly to illustrate what the effects of negative electricity prices might be, rather than being a rigorous prediction of where these negative prices might occur.

2.1. Daily simulation

The electricity price used to generate the typical daily electricity prices is the UK Market Index Price (spot price) 2013. The 2013 UK Market Index Price can be downloaded [17]. To generate a set of typical daily prices, the mean price at each half-hour period for each day of the year 2013 was calculated, accounting for one short day (Sunday, 31st March) and one long day (Sunday, 27th October). For this typical daily price, the minimum price for a half-hour period is £35/MWh and the maximum price is £66/MWh. To illustrate the effect of negative electricity prices, the typical daily prices are modified by shifting the prices between 3 am and 6 am by −£70/MWh so that they become negative and roughly equal in magnitude.

The model algorithm is used to calculate the maximum arbitrage revenue available to an energy storage device with set capacity (200 kWh) and charging and discharging power limits (50 kW) and a given round-trip efficiency. Figure 3 shows the optimal charging/discharging schedule of a 75% EES device with the unmodified typical daily electricity prices. As is intuitive, the model charges during the times of lowest electricity prices and discharges at the time of the highest prices. This optimum schedule generates a modest £2.32 over the 'typical' day.

Figure 4 shows a surface plot of the total revenue generated over the average day when the energy storage efficiency is varied from 5% to 100% and the capacity is varied from 25 to 250 kWh (0.5–5 h). It can be seen that a higher capacity and higher round-trip

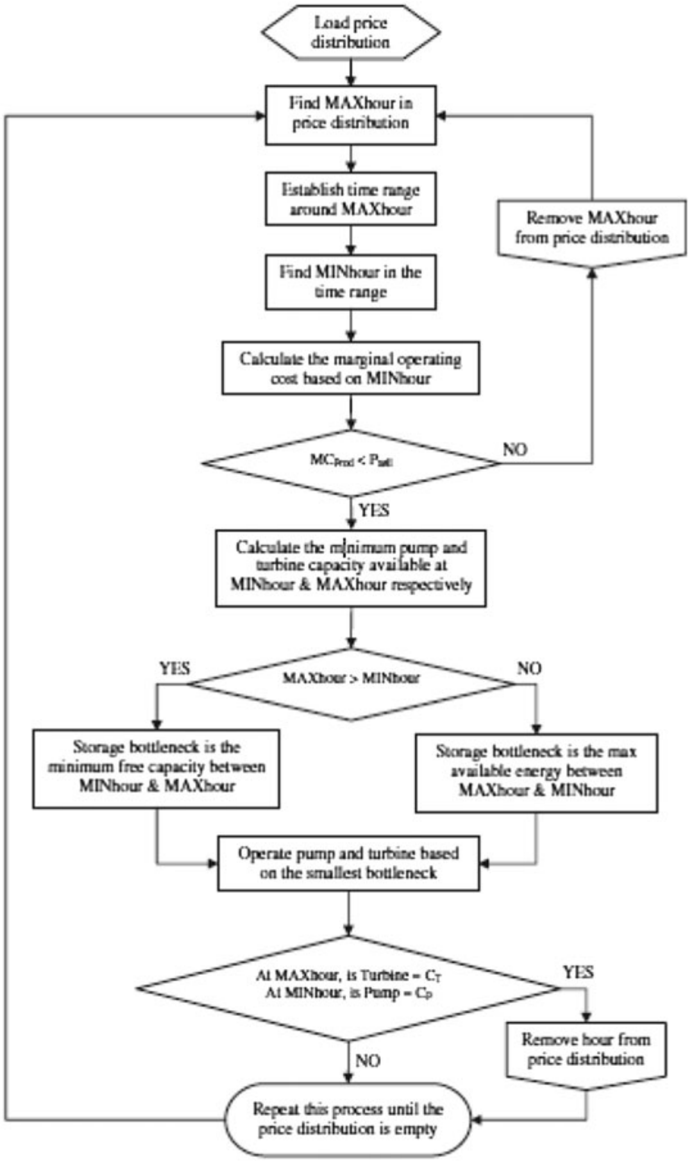

Figure 2. Flow chart of the optimisation model operation.

efficiency lead to larger revenues. No revenue can be generated with a round-trip storage efficiency below around 50%. This is to be expected as during the example typical day the minimum price for electricity was £35/MWh and the maximum was £70/MWh. Hence, a storage device with less than 53% efficiency could not exploit the maximum price differential observed and thus could not generate any revenue from arbitrage, regardless of the capacity of the store.

We now explore the case in which the price of electricity between the hours of 3 and 6 am is modified by −£70/MWh, so that the prices at these times become negative. Figure 5

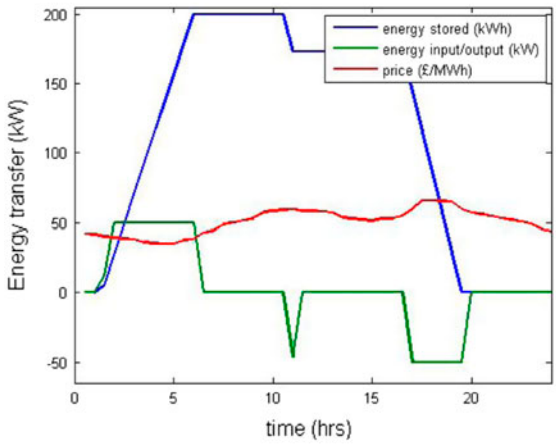

Figure 3. Optimal charging/discharging schedule for a 75% efficient ES device using the average daily spot market electricity price 2009.

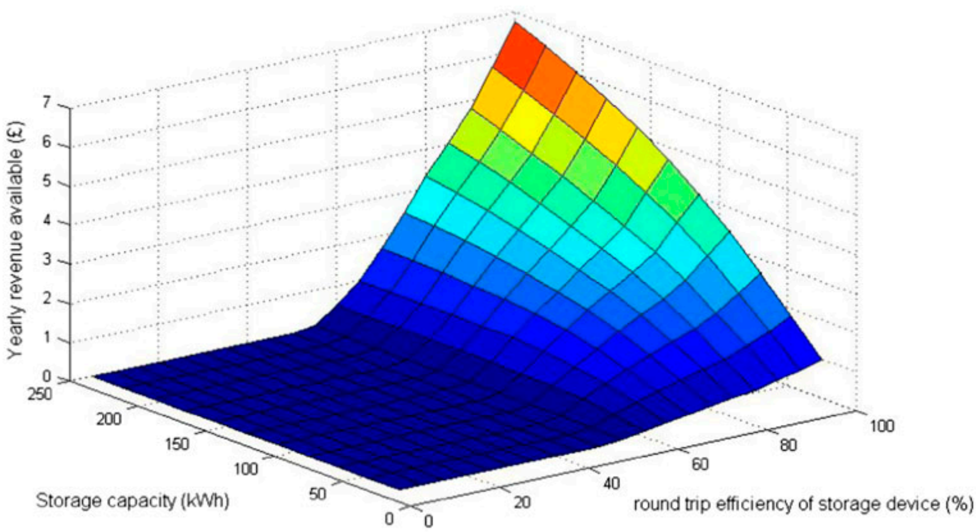

Figure 4. Total revenue generated in pounds sterling by the action of a storage system with charging/discharging limits of 50 kW.

illustrates the modified typical daily prices. The optimum schedule of operation of the same 75% efficient EES device as used in figure 4 above can now generate a revenue of £12.82 – nearly a 500% increase in available revenue.

Figure 6 shows a surface plot equivalent to that in Figure 4 but using the modified electricity prices (as shown in Figure 5). It is firstly notable that with the presence of negative electricity prices there is no efficiency threshold for the ability to generate revenue. This is to be expected as now storage is being paid for both charging and discharging, and so can generate revenue even without being able to return any electricity during discharge. Interestingly, it is also observed that at low storage capacity to power ratios, inefficient storage devices have larger maximum available revenues compared to higher efficiency devices.

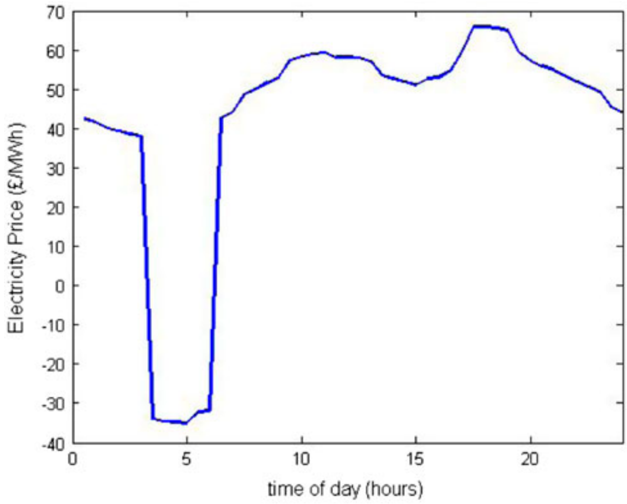

Figure 5. Illustrating the ‘typical’ daily prices modified to include some negative prices, where it can be seen that between 3 and 6 am, prices are negative.

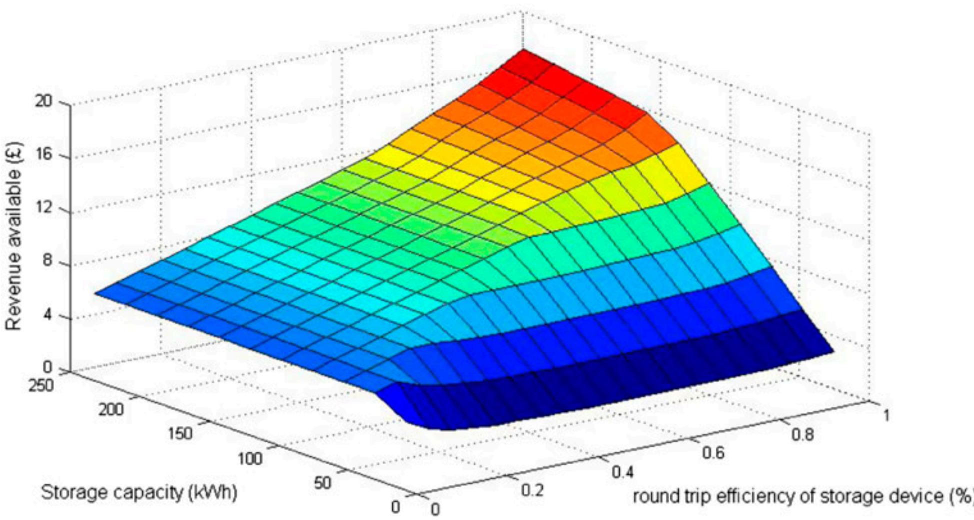

Figure 6. Revenue available when price file input is altered so that the prices between 3 and 6 am are negative. Note that now a device with any efficiency can derive revenue.

This is caused by their lower efficiency, which allows them to exploit more periods of negative electricity prices. As the storage capacity increases this effect is negated and the higher efficiency devices always have higher available revenues.

2.2. Yearly simulation

For the yearly simulation, the 2013 market index (spot) price data are again used. Firstly, the effect of device efficiency against available arbitrage revenue is demonstrated on the yearly unmodified 2013 spot prices. Then the 2013 spot market price is modified so that the lowest 56 h of electricity prices during the year are assigned a negative price, by subtracting an offset value. Figure 7 shows the 2013 yearly spot prices and the modified prices when the offset value is £50/MWh. In the original price data, there were three periods (1.5 h) on the 15 January 2013 which had £0/MWh price. It is thought that these were missing values rather than zero price events, given the relatively high prices immediately before and after these periods, and given that they occurred on a Tuesday morning between 9:30 and 11 am. Accordingly, they were assigned the average of the prices from 9 to 9:30 am and 11–11:30 am.

Using the original electricity prices for 2013 and again simulating a 75% efficient 200 kWh 50 kW energy storage device, we find the available revenue over the course of the year is £1317. Figure 8 shows how this varies as the round-trip efficiency of the device is varied. We observe that the maximum available revenue is highly correlated with EES efficiency.

We then run the simulation (again for a 200 kWh 50 kW as well as a 100 kWh 50 kW device) with the 2013 spot prices but the minimum priced 56 h are made negative by subtracting an offset value. These minimum 56 h represent 0.64% of the hours in the year. The effect of the offset value is investigated as well as EES device efficiency. Figure 9(a) and (b) shows the results of the simulations. The *y*-axis shows the offset used and the *x*-axis is the simulated EES efficiency. Table 1 shows the average value of the negative price periods throughout the year for each offset value.

The figures illustrate that the presence of a small amount of negatively priced periods leads to a significant increase in the revenue available to storage operators. This is true even if these prices are on average only slightly negative and increases with the 'degree of negativity'. For example, the 75% efficient 200 kWh 50 kW has an increase in available yearly revenue of 5.8% (from £1317 to £1393) when the lowest 56 h of yearly prices are offset by −£30/MWh and an increase of 13.7% to (from £1317 to £1497) when they are offset by −£70/MWh. The figures also show that predominantly higher efficiency devices have higher available arbitrage revenues. The only exception to this in the simulations is the case of EES devices with small capacity to power ratios and efficiencies less than 40%.

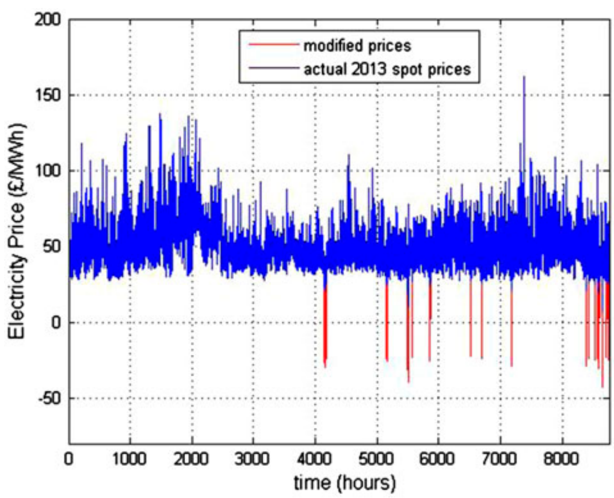

Figure 7. Comparing the original and 'modified' yearly prices.

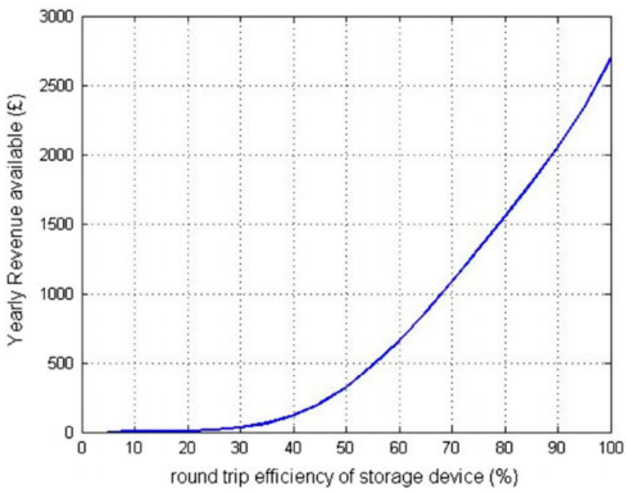

Figure 8. Arbitrage revenue available for a 200 kWh 50 kW energy storage device. As can be seen the revenue available is heavily dependent on the device efficiency, with low-efficiency devices having very little revenue available.

3. Discussions and conclusions

It is clear that when all electricity prices are positive, arbitrage favours the use of more-efficient EES devices. Indeed, with an efficiency below the ratio of the lowest to highest electricity prices, there is no ability to generate revenue once the round-trip efficiency losses have been accounted for. The introduction of negative electricity prices changes this, however, as storage is paid to charge as well as discharge and this allows even the most inefficient devices to gain some revenue. Our simulations suggest that it only takes a small number of periods with negative prices to lead to a significant increase in the revenue available to EES. This is because when EES is paid to charge as well as discharge, the value of each MWh passing through the storage device is increased compared to the case of exploiting typical daily price differentials.

As discussed in Section 2, it is possible that during a sustained period of stable negative electricity prices energy storage could derive revenue by charging and discharging (at these

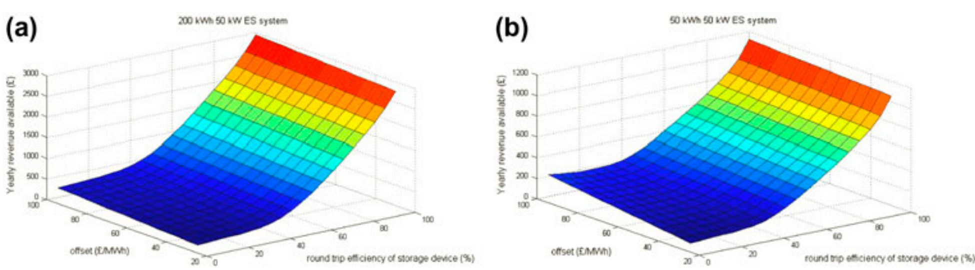

Figure 9. (a) surface plot of revenue available for a 200 kWh 50 kW storage system with the modified 2013 spot prices. (b) equivalent plot for a 50 kWh 50 kW device.

Table 1. Offset and the average price of the negative electricity prices with that offset.

Offset (£/MWh)	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Average negative price value (£/MWh)	−6.9	−11.9	−16.9	−21.9	−26.9	−31.9	−36.9	−41.9	−46.9	−51.9	−56.9	−61.9	−66.9	−71.9	−76.9

negative price periods). This represents an extreme case, technically possible, but unlikely to appear in the real world.

Most previous articles on energy storage and arbitrage suggest efficiency is an essential factor in a device's ability to generate revenue [1,2], and so devices intended to profit from this method should have the maximum possible efficiency. The work reported here concurs when all electricity prices are positive; but in the presence of a small number of negative electricity prices even low-efficiency EES devices can derive revenue from electricity arbitrage. It is also possible that these negative prices can encourage inefficiency in EES devices when storage is acting in an economically rational manner (buying low-cost and selling high-cost electricity). Our simulations suggest, however, that this is unlikely to be the case given the possible low frequency of negative prices. Devices used for electricity arbitrage are also anticipated to require high energy capacity to power ratios and our simulations suggest that inefficiency is not promoted for these devices. For the yearly simulations, the only situation in which lower efficiency EES devices have larger available revenues is for very small energy capacity to power ratios and very inefficient devices (see figure 9(b)).

Therefore, negative electricity prices can be viewed as additional bonus revenue for EES, given the likely low frequency of these events. This suggests that the market still favours efficient energy storage devices over their less-efficient counterparts.

In short, negative spot prices are always likely to provide additional revenue to energy storage operators, but because negative spot prices are likely to be infrequent, they will probably not have a major impact on technology choices.

Of course, the participation of enough energy storage capacity in the electricity market would stop prices from reaching negative levels. Competing storage devices would bid to charge on low-cost electricity, driving the prices up. If this level of storage was to be achieved, then it could be regarded as a market success and the energy network would have a sufficient level of flexibility.

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