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ECONOMIC VIABILITY OF DOMESTIC BATTERY STORAGE PARTICIPATION IN BRITISH FLEXIBILTY MARKETS

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Abstract

Curbing emissions to avoid the worst impacts of climate change is likely to lead to a significant increase in electricity demand due to the electrification of heating and transportation, and a decrease in the balancing reserve due to a decrease in the number of gas turbines. To alleviate the significant network investment costs and the fall in balancing resources, both distribution network operators and the system operator in Great Britain have created markets for behind-the-meter flexibility. For domestic battery storage to play a meaningful role in flexibility markets, it must be beneficial to the households who choose to finance and install it. In this paper we examine the value of domestic battery storage systems, both with and without associated PV installations. We show that domestic battery storage is a financially worthwhile investment for households, and that participating in network operator and system operator flexibility markets can be lucrative. Finally, we show that domestic PV installations have a negative value when accounting for the capital investment. However, if a household wanted to install PV for non-financial reasons, investing in a battery alongside the PV gives the installed system a positive value.

1. Introduction

The UK's commitment to reach net zero emission greenhouse gas emissions by 2050 will require significant changes to the energy system. All fossil fuel powered cars, vans and heating will need to be replaced [1]. Meanwhile, electricity generation from unabated gas turbines must cease [2]. This growth in electricity demand will require significant investment in electricity networks [3]. The reduction in gas turbine numbers will limit the system operator's options for system balancing [4]. Both the system operator and distribution network operators (DNO) in Great Britain are considering using domestic flexibility to help alleviate these problems. To assess the benefits of installing photovoltaic (PV) solar panels and domestic batteries to participate in system operator and DNO flexibility markets, this paper calculates the payback period, net present value and internal rate of return of domestic battery storage systems with and without co-located PV systems.

Previous work has considered how to optimally schedule energy storage [5, 6], the value of co-locating storage and generation [7-9], and the benefit to the energy system [10, 11]. Households have a choice about whether to install storage. It is important to demonstrate the value of storage to the households who must choose to finance and install it. The smart meter roll-out has shown that technology diffusion to households can be challenging [12]. In this paper we show that domestic batteries are a financially worthwhile investment for households, accounting for the capital investment. We further show that while domestic batteries have a positive net present value based solely on time-of-use tariffs, their value increases if they can participate in system operator and/or DNO flexibility markets.

The rest of this paper is structured as follows. Section 2 provides detail of the model developed for this study. Section 3 provides the results. Section 4 provides concluding remarks.

2. Methodology

The model presented in this paper is of a household which optimises its energy use to minimise its energy cost. The model aims to estimate the value of optimising energy use when subjected to time-of-use import and export tariffs and selling flexibility into system and network operator flexibility markets. Four household profiles were modelled. A 24-hour period was simulated with 30-minute-long settlement periods.

2.1. *Model description*

The household is modelled using a mixed integer linear programming problem. The problem was coded in Python using the Pyomo package [13] and solved using the 'glpk' solver. The objective function is described in equation (1):

$$\min_{i\in I}(\lambda_i^{ToU} \times E_i^{net} - \lambda_i^{BM} \times \Delta E_i^{BM} - \lambda_i^{DNO} \times \Delta E_i^{DNO}) \quad (1)$$

Subject to the constraints in equation (2):

$$\begin{cases} SoC_i = SoC_{i-1} + \Delta \mathrm{SoC}_i^+ + \Delta SoC_i^- \\ \Delta SoC_i^+ \times eff = E_i^{imp} + E_i^{PV} + \Delta E_i^{BM,pos} \\ \Delta SoC_i^- \times eff = E_i^{load} + E_i^{exp} + \Delta E_i^{BM,neg} + \Delta E_i^{DNO} \\ chgLim \geq E_i^{imp} + E_i^{PV} - \Delta E_i^{BM,pos} \\ dischgLim \leq E_i^{load} + E_i^{exp} + \Delta E_i^{BM,neg} + \Delta E_i^{DNO} \\ \Delta SoC_i^+ | \Delta SoC_i^- = 0 \end{cases} \quad (2)$$

Where:

$I = set\ of\ 48\ settlement\ periods$
$\lambda_i^{ToU} = time\ of\ use\ import\ or\ export\ tariff$
$\lambda_i^{BM} = balancing\ mechanism\ cash\ out\ price$
$\lambda_i^{DNO} = DNO\ flexibility\ market\ price$
$E_i^{net} = net\ imported\ energy$
$E_i^{imp} = imported\ energy\ into\ battery$
$E_i^{exp} = exported\ energy\ from\ battery$
$E_i^{PV} = energy\ from\ PV\ system\ into\ battery$
$E_i^{load} = energy\ to\ load\ from\ battery$
$\Delta E_i^{BM,pos} = energy\ absorbed\ by\ battery\ for\ balancing\ mechanism$
$\Delta E_i^{BM,neg} = energy\ released\ by\ battery\ for\ balancing\ mechanism$
$\Delta E_i^{DNO} = energy\ absorbed\ by\ battery\ for\ DNO\ flexibility\ market$
$SoC_i = battery\ state\ of\ charge$
$\Delta SoC_i^{+} = increase\ in\ battery\ state\ of\ charge$
$\Delta SoC_i^{-} = decrease\ in\ battery\ state\ of\ charge$
$eff = battery\ charge\ and\ discharge\ efficiency$
$chgLmt = battery\ maximum\ charge\ power$
$dischgLmt = battery\ maximum\ discharge\ power$

2.2. *Inputs and datasets*

Where possible, real data was used to make the outputs as realistic as possible. The sources of input data and any transformation performed on the data are described in this section.

2.2.1. Load and generation data: The load is measured smart meter data from London, UK [14]. The PV generation is measured data from south-east England [15]. Four, one day long profiles with 30-minute settlement periods have been extracted from this data and assigned to each of the four households. The PV systems have a 3 kW installed capacity.

2.2.2. Time-of-use import and export tariffs: Agile Octopus time-of-use import and export tariff data from London are used [16].

2.2.3. Energy system operator flexibility market: Historic balancing mechanism cash out prices are used as indicative of the value of flexibility to the system operator [17]. Domestic flexibility may participate in the new demand flexibility service [18]. However, this service is still in trial, and no pricing data is available.

2.2.4. Distribution network operator flexibility market: For the DNO flexibility market there are only historic records of bids which were accepted [19]. There is no data on the frequency with which accepted bids were dispatched. For this model a representative DNO flexibility market price profile has been created based on accepted bid data. This profile assumes that the flexibility market is available between 07:30 and 19:30. The market pays a 5 GBP/MWh availability payment between those hours and 40 GBP/MWh if the flexibility is activated. In this model the flexibility is activated between 17:00 and 19:30 to coincide with peak electricity demand.

2.2.5. Battery: The battery in the model is based on a Tesla Powerwall 2 because they have a low cost per kWh compared to other domestic batteries [20, 21]. The parameters used in this model are:

- Useable energy = 13.5 kWh
- Maximum charge & discharge power = 3.3 kW
- Charge & discharge efficiencies = 0.95 (90% round trip efficiency)

2.3. *Cases*

A total of 10 cases were run for each of the four household profiles with different load and PV generation, giving a total of 40 model runs. Table 1 shows the cases run. A base case with no PV or battery was run for comparison. A case with PV but no battery was run to test the value of generation without flexibility (case 1). Eight cases were run to estimate the value of flexibility (cases 2-9). These cases tested each combination of participation in the system operator and DNO flexibility markets, with and without PV. The results presented are the mean of the four runs for each case, to reduce the effect of any eccentricities of load or PV generation profile.

2.4. *Analysis*

To assess the benefits of installing PV and domestic batteries to participate in system operator and DNO flexibility markets, the payback period, net present value (NPV) and internal rate of return (IRR) were calculated for each of the nine test cases. For this analysis it was assumed that the cost of the 3 kW PV system was £6,000 and the 13.5 kWh domestic battery was £10,000. Both figures are based on prevailing rates in the UK, including installation [22, 23]. The lifespan of both the battery and solar panels is assumed to be 20 years [24, 25].

For the NPV calculation, a discount rate of 5% was used. This is slightly below the prevailing rate for a home improvement loan in the UK [26]. The reduced rate is reflective of the fact that the 2022 base rate is higher than historically observed due to the ongoing upheaval in global energy markets, and is likely to fall over the medium term [27]. The IRR, the discount rate at which the NPV is zero, was calculated to assess the sensitivity of each case to interest rate changes.

Table 1 Model cases

Case	Battery	PV	Time-of-use tariffs	Balancing mechanism	DNO flexibility market
Base	No	No	Yes	No	No
1	No	Yes	Yes	No	No
2	Yes	No	Yes	No	No
3	Yes	Yes	Yes	No	No
4	Yes	No	Yes	Yes	No
5	Yes	Yes	Yes	Yes	No
6	Yes	No	Yes	No	Yes
7	Yes	Yes	Yes	No	Yes
8	Yes	No	Yes	Yes	Yes
9	Yes	Yes	Yes	Yes	Yes

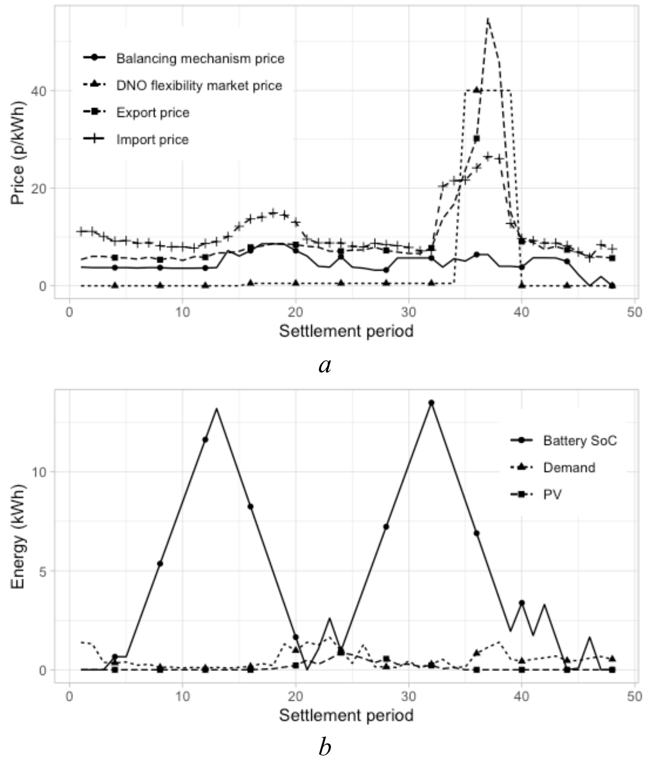
3. Results

The results of the model runs show that providing flexibility is a profitable service for the household, more so than generating energy. Value stacking, participating in more than one flexibility market, increases the revenue from providing flexibility. The DNO flexibility market is more profitable than the balancing mechanism. Participating in the DNO flexibility market increases revenue 135% compared to just time-of-use tariffs, participating in the balancing mechanism increases revenue 60%. Participating in both the DNO flexibility market and the balancing mechanism increases revenue 178% over time-of-use tariffs alone. Figure 1 shows the prices, demand and generation profiles, and battery state of charge for a model run from case 9, when the household participates in both the DNO flexibility market and balancing mechanism. Table 2 provides numerical results.

3.1. PV reduces the value of the investment

When accounting for the capital investment and financing costs, PV has a negative return on investment in all scenarios. Case 1 shows that a PV installation, without a battery and only meeting self-consumption or exporting through the time-of-use tariff, has a negative net present value at a 5% discount rate, and would need a negative discount rate to break even.

In all scenarios with a battery, comparing the case with PV to the case without PV (i.e. case 2 compared to 3, 4 compared to 5, etc.), the PV installation reduces the net present value of the investment. This implies that the market puts more value on flexibility than on energy generation, and PV is not a good investment for households in Britain. However, if a household wanted to invest in PV panels for reasons other than profit, installing a battery with the PV panels and participating in flexibility markets makes the whole installation profitable, although less so than a battery without PV. At discount rates below 3%, a PV and battery combination has a positive NPV based only on time-of-use tariffs. If the household can participate in the balancing mechanism and DNO flexibility markets, the NPV is positive at discount rates below 15%.



a

b

Figure 1 Example model run from case 9 showing (a) prices from the balancing mechanism, DNO flexibility market, and import and export tariffs; and (b) the battery state of charge, and the demand and PV generation profiles

Table 2 Numerical results

Case	Financial benefit over base case (GBP/year)	Payback period (years)	Net present value (GBP @ 5% discount rate)	Internal rate of return
1	£ 237	25.3	£ (3,048)	-2%
2	£ 847	11.8	£ 559	6%
3	£ 1,082	14.8	£ (2,512)	3%
4	£ 1,363	7.3	£ 6,987	12%
5	£ 1,610	9.9	£ 4,066	8%
6	£ 1,997	5.0	£ 14,883	19%
7	£ 2,232	7.2	£ 11,820	13%
8	£ 2,359	4.2	£ 19,403	23%
9	£ 2,606	6.1	£ 16,482	15%

3.2. Energy storage has value under all scenarios

The installation of a battery without PV has a positive NPV at a 5% discount rate in all cases. Participating in the balancing mechanism or DNO flexibility market significantly increases the value of the battery. However, the DNO flexibility market brings more value than the balancing mechanism. Participating in both brings more value than either individually.

A domestic battery may be financeable based just on participation in time-of-use tariffs, with an IRR of 6%. If the household can participate in the DNO flexibility market and/or balancing mechanism the IRR is high (12-23%), and so the household should easily be able to profit from the installation after capital costs.

4. Conclusion

This paper has presented a mixed integer linear programming optimisation model to estimate the value of domestic battery storage. The model tests the value of participating in time-of-use import/export tariffs, DNO flexibility markets and the balancing mechanism. The model also tests whether PV is beneficial when co-located with domestic battery storage.

The results of the model show that the installation of a domestic battery is a profitable investment after accounting for capital costs. However, a domestic scale PV installation is not profitable at current costs. While the battery has a positive NPV just using time-of-use tariffs, participating in DNO flexibility markets and/or the balancing mechanism significantly increases it value, with the DNO flexibility market being more profitable than the balancing mechanism.

The model presented in this paper assumes that the household is able to participate in both a DNO flexibility market and the balancing mechanism. To participate in a DNO flexibility market, a household must be below a piece of equipment which has reached its operating capacity (a network constraint). These network constraints tend to be relatively short lived (a small number of years), because as demand continues to grow the DNO will be forced to reinforce them eventually. Therefore, not all households will be able to participate in DNO flexibility markets. Households that can participate, will only be able to do so for a relatively short period of the life of a domestic battery. It is therefore important to note that the DNO flexibility markets are not critical to making domestic storage profitable. Participation in a DNO flexibility market is highly profitable for those households able to do it, but the battery is still a worthwhile investment without the DNO flexibility market.

Unlike DNO flexibility markets, the balancing mechanism does not have any geographical requirements, and would therefore be theoretically open to all households. However, the balancing mechanism, and new demand flexibility service, have 1 MW minimum bid volumes. This means that households wishing to participate would have to do so through an aggregator. The model in this paper does not account for any fees from the aggregator, which would reduce the profitability of participation in the balancing mechanism.

The balancing mechanism also penalises participants who do not provide the response they committed to. The model in this paper does not include any forecasting errors or associated penalties. Forecasting errors are almost certain to occur. The associated penalties will reduce the profit from participating in the balancing mechanism. It is not yet clear what penalties, if any, will exist in the new demand flexibility service.

Future work could usefully extend the model presented in this paper to examine the effect of aggregation and forecasting error penalties on the value of domestic storage. These are likely to be important costs to consider when making domestic storage investment decisions. Some loads which result from the energy system decarbonisation, such as electric vehicles, may also be able to participate in flexibility markets. The model in this paper could be usefully extended to consider the profitability of flexible loads in Great Britain.

5. Acknowledgements

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