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Domestic photovoltaic systems, battery storage, and the economic impact of time-of-use electricity pricing

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***Abstract*— Time-of-use electricity pricing is characterised by high 'peak' prices, generally throughout the day and evening, and low 'off-peak' prices, generally at night. Consumers can benefit from time-of-use pricing provided their ratio of peak-to-off-peak electricity consumption is less than a ratio of the relative prices of the two tariffs. To alter their consumption ratio, consumers can time-shift their demand, known as demand response. Consumers with grid-connected PV systems, however, already have reduced net demand during the day-time peak, due to the PV generation. The first question of interest to this paper is whether consumers with PV systems would benefit financially from switching to time-of-use pricing even if they do not engage in demand response. There remains the concern, however, of high prices during the evening peak, when the PV is not generating. Consumers unwilling or unable to engage in demand response during these periods can install battery storage systems, which are charged during the day and discharged during the evening. Two additional questions are therefore: what is the additional financial benefit of battery storage to PV systems with time-of-use pricing and are batteries financially viable for domestic consumers with PV? These questions are answered using data from real dwellings with PV in the UK and simulating power flows using a published lead-acid battery model. Economic impacts are measured for a range of time-of-use pricing tariffs from the UK and Ireland. Results indicate that PV has little effect on the financial benefit of time-of-use pricing with day period prices that are similar to the flat rate price. For tariffs where the day period price is greater than the flat rate price, PV improves the benefit, but not enough to make it an economic choice for the average consumer. Battery storage improves the financial return, but this is not enough to make the business case positive. Even using optimistic assumptions, such as lossless batteries and high electricity price increase, system costs need to be lowered by at least 33.5% for lead-acid systems, and 195% for lithium ion systems.**

Keywords-domestic; PV system; time-of-use pricing; demand response; battery.

I. INTRODUCTION

Demand response consists of consumers time-shifting electricity demand in response to a signal, usually in the form of a financial incentive, such as an electricity tariff with variable pricing ('dynamic pricing'). Demand response will be of increasing value in integrating the high penetrations of renewable energy and low-carbon technologies that are expected to be connected to electrical power systems in the future [1,2].

Dynamic pricing is one of the principle tools used to secure demand response, and engineers concerned with the secure operation of low-carbon power systems envision a future with domestic consumers responding to dynamic pricing closely correlated with wholesale electricity market prices, known as 'real-time pricing' [3,4].

In many current markets, however, the majority of domestic consumers have tariffs with electricity prices that do not vary in time ('flat rate tariffs'). For example, over 80% of domestic consumers in the UK are on a flat rate tariff [5].

Time-of-use pricing is a form of dynamic pricing where the day is divided into periods of high and low prices, generally referred to as 'peak' and 'off-peak'. These periods are generally static, with prices and durations that are known in advance. Time-of-use pricing reflects wholesale prices better than flat rate tariffs, but is not as variable or complex as real-time pricing, and so can be viewed as a 'stepping stone' towards real-time pricing for domestic consumers on flat rate tariffs.

Fig. 1 shows the price profiles for three examples of time-of-use pricing. Economy 7 has been used for decades in the UK to encourage demand during the night and flatten the demand profile [6], while the two Irish time-of-use tariffs were recently trialed as part of the Irish Electricity Smart Metering Customer Behaviour Trials [7]. The Irish tariffs divide the day into three periods, with a 'day' (or 'shoulder') period between the peak and off-peak periods. This paper follows the Irish tariff convention for timing of time-of-use pricing periods, as described in Table 1. Note that the Economy 7 off-peak period has therefore been adjusted here to align it with the Irish off-peak period. This will not affect the conclusions of this paper. Prices for the tariffs are detailed in Table 1.

TABLE I. PRICES FOR THREE TYPES OF TIME-OF-USE PRICING.

Period	Hours	Economy 7	Irish time-of-use A	Irish time-of-use D
Off-peak	11pm to 8am	6.03 p/kWh	12 c€/kWh	9 c€/kWh
Day	8am to 5pm, 7pm to 11pm	16.24 p/kWh	14 c€/kWh	12.5 c€/kWh
Peak	5pm to 7pm	16.24 p/kWh	20 c€/kWh	38 c€/kWh

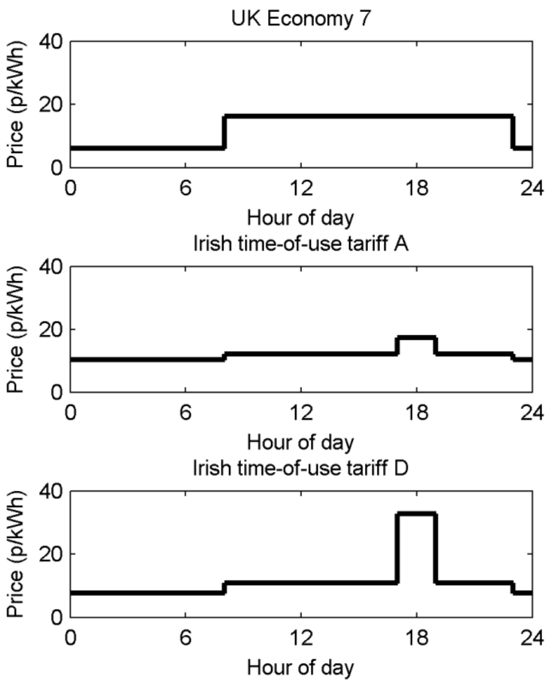

Figure 1. Price profiles for the time-of-use tariffs considered in this paper.

Consumers with time-of-use pricing can benefit financially by shifting demand away from the peak and day periods. While this can be achieved by changing demand practices, consumers with PV systems already have reduced imports from the grid during the day due to the PV generation. The first research question of this paper is therefore whether consumers with PV systems would benefit financially from switching to time-of-use pricing, even if they do not engage in demand response.

While PV systems may reduce imports during the day, they produce relatively little during the evening peak, when prices are still high, as with the Irish time-of-use D tariff shown in Fig 1. To deal with these periods, consumers who are unable or unwilling to engage in demand response themselves can consider the option of installing a battery storage system. The concept is to charge the battery during the day using excess PV generation, and discharge the battery during the evening to reduce expensive imports from the grid.

This type of system exploits the specific commercial opportunity of trading exported electricity, at a relatively low price, for imported electricity, at a relatively high price. It is applicable to consumers with PV in countries that have feed-in tariffs with export prices that are lower than typical import prices, such as the UK, or German systems installed after 2011. Indeed, battery systems for this purpose are of considerable interest in the German market, with 68 systems commercially available from 30 suppliers in 2012 [8].

Battery storage systems for domestic PV tend to be relatively expensive, however, and a previous study by the authors found no business case for the use of battery storage in domestic PV systems in the UK [9]. The second question addressed by this paper is therefore what is the financial benefit of installing battery storage to a PV system with time-of-use pricing? Following on from this is the paper's third and final question: are batteries financially viable for domestic consumers with PV?

II. METHOD

A. Visualising time-of-use benefits with energy-ratios

The first research question is concerned with determining whether a group of consumers (those with PV in this case) would benefit from switching from a flat rate tariff to time-of-use pricing. To help address this question, consider the specific case where a consumer would be neither better off nor worse off by switching to time-of-use pricing, in which case:

$$C_{flat} = C_{TOU} \tag{1}$$

Where C_{flat} is the total cost of their electricity over a given period of time on a flat rate tariff and C_{TOU} is the corresponding cost on a time-of-use tariff. Re-writing this in terms of energy consumption and prices during the tariff periods gives:

$$E_{tot}p_f = E_p p_p + E_d p_d + E_o p_o \tag{2}$$

Where E_{tot} is the consumers total electricity consumption, p_f is the flat rate price, and E_p, E_d, E_o, and p_p, p_d, p_o are the energy consumptions and prices during the peak, day and off-peak periods respectively. As the total electricity consumption is the sum of the consumptions during the peak, day, and off-peak periods, this can be re-written to provide a linear function relating ratios of energy consumptions to relative prices, as follows:

$$E_p(p_p - p_f) + E_d(p_d - p_f) + E_o(p_o - p_f) = 0 \tag{3}$$

$$\frac{E_p}{E_o}(p_p - p_f) + \frac{E_d}{E_o}(p_d - p_f) + (p_o - p_f) = 0 \tag{4}$$

Replacing the 'energy-ratio' terms with y and x,

$y = \frac{E_p}{E_o}$, and $x = \frac{E_d}{E_o}$

Gives,

$$y(p_p - p_f) + x(p_d - p_f) + (p_o - p_f) = 0 \tag{5}$$

$$y = \frac{(p_f - p_d)}{(p_p - p_f)}x + \frac{(p_f - p_o)}{(p_p - p_f)} \tag{6}$$

Knowing the prices for the flat rate tariff and time-of-use pricing therefore allows 'breakeven' lines to be plotted which indicate the energy-ratios that would produce no change in cost. Fig 2. shows breakeven lines for the three types of time-of-pricing described previously. The gradient of the Economy 7 line is negative because the day period price, p_d, is larger than the flat rate price, p_f, in this case 16.24 p/kWh compared to 11.77 p/kWh [10]. The Irish time-of-use pricing has positive gradients because the day period prices (14 c€/kWh and 12.5 c€/kWh for tariff A and D respectively) are smaller than the flat price of 14.1 c€/kWh [7].

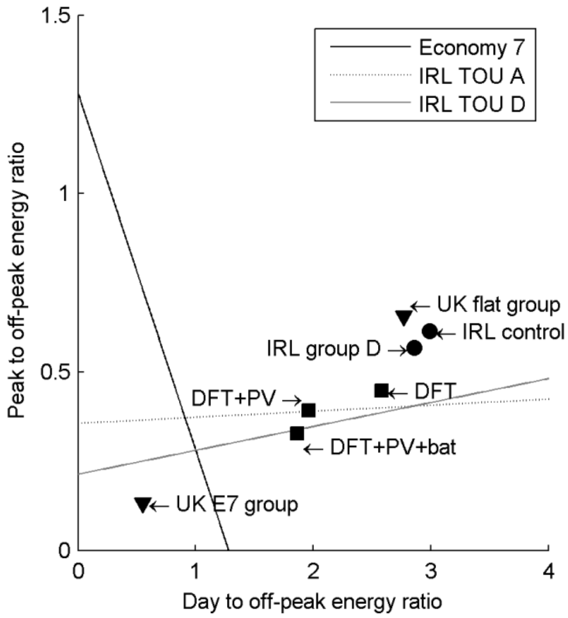

Figure 2. Energy-ratios for groups in relation to lines that indicate values that would produce no change in cost for three types of time-of-use pricing.

A consumer will be better off on time-of-use pricing if their energy-ratios take them below the breakeven line. Fig. 2 shows actual energy-ratios for several groups of consumers. 'UK flat group' and 'UK E7 group' show values for UK consumers on flat rate tariffs and Economy 7 respectively. These are calculated from the Elexon Class 1 and 2 demand profiles [11]. The Economy 7 group appears below the Economy 7 breakeven line, indicating that they are financial better off on the Economy 7 tariff compared to the flat rate. 'IRL control' and 'IRL group D' show energy-ratios for the control group, who were on a flat rate tariff, and the group on the time-of-use tariff D from the Irish Smart Meter Customer Behaviour Trial [7]. Group D has lower energy-ratios than the control group, which indicates that they reduced demand during peak and day periods, or increased off-peak demand, or both. The figure also shows that group D would have been better off on the flat rate tariff rather than the time-of-use pricing. The 'DFT' groups are explained later.

PV systems produce power predominantly during the day period, and so intuitively one would expect the presence of PV to shift consumers horizontally to the left on the energy-ratio figure. Given the positive gradients of the Irish breakeven lines, however, it can be said already that this might not be of benefit.

A battery system will act to reduce imports predominantly during the evening peak, and so intuitively one would expect the presence of a battery system to shift consumers vertically downwards. Given the breakeven lines, and not considering the cost of the battery system, it can be said that this would be of benefit for all tariffs considered here.

B. *Description of data and benefit calculations*

To calculate financial benefits of switching from flat rate to time-of-use pricing, data is used from real domestic dwellings with PV systems in the UK. The data consists of one year of metered generation, exports and imports at 5 minute resolution for 15 dwellings located in the UK with PV systems ranging in size from 2.03 kW_{peak} to 3.29 kW_{peak}. The data comprises one of the monitored sites of the UK Photovoltaic Domestic Field Trial [12], and is the same as one of the sites that was used in the authors' previous study of batteries in domestic PV systems, where further description of the data can be found [9]. The group is assumed to be on a UK feed-in tariff with an export price of 3.2 p/kWh. This group is called the 'PV group' in the following.

Using the data for one year, the benefit of switching to time-of-use is calculated as:

$$\Delta B_{TOU} = C_{flat} - C_{TOU} = \sum_n \left(E_{i,n} p_f - E_{i,n} p_{TOU,n}\right) \quad (7)$$

Where ΔB_{TOU} is the benefit, $E_{i,n}$ is the imports in kWh for the 5 minute interval n, and $p_{TOU,n}$ is the time-of-use price in interval n. For Economy 7, the applicable flat rate price is taken to be 11.77 p/kWh, while for Irish time-of-use pricing it is taken to be 14.1 c€/kWh. A Euro to Sterling conversion of 0.861 is used.

To calculate the benefit of adding a battery to a PV system with time-of-use pricing, the same model is used as fully described in a previous publication [9]. The model simulates dwelling power flows for the 15 dwellings using a realistic battery model. A 430 Ah (20.64 kWh) lead-acid battery is chosen for this study. A 40% depth of discharge is used, resulting in a relatively large useable capacity (8.26 kWh) compared to commercially available systems [8].

The battery will act to reduce exports to the grid at an opportunity cost, thus reducing income, as well as reducing imports from the grid, reducing costs. The benefit is calculated as:

$$\begin{aligned}\Delta B_{bat} &= \text{Change in income} - \text{Change in costs} \\ &= \left(M_{PV+bat} - M_{PV}\right) - \left(C_{TOU+bat} - C_{TOU}\right) \\ &= \sum_n \Big[\left(E_{e,PV+bat,n} p_e - E_{e,PV,n} p_e\right) \\ &\qquad - \left(E_{i,bat,n} p_{TOU,n} - E_{i,n} p_{TOU,n}\right)\Big]\end{aligned} \quad (8)$$

Where M_{PV+bat} and M_{PV} are incomes for PV system with and without battery respectively, $C_{TOU+bat}$ is the electricity cost with battery and time-of-use pricing, $E_{e,PV+bat,n}$ and $E_{e,PV,n}$ are exports with and without battery during interval n, p_e is the export price, and $E_{i,bat,n}$ is the import with battery during interval n. Note that income due to feed-in tariff generation payments, applicable to the UK for example, have been left out as the battery does not affect these. As with the time-of-use benefit, this will be calculated over a whole year using the data for the 15 dwellings.

To consider whether batteries are financially viable for domestic consumers with PV, a target upfront system cost can be calculated, which can be compared to current system costs in the market, as:

$$C_{bat} = \sum_m \eta \, \Delta p \, E_{e,annual} \frac{(1+r_i)^m}{(1+r_d)^m} \quad (9)$$

Where C_{bat} is the target upfront system cost that will result in a net present value of zero, η is the system round-trip efficiency of the battery storage system including converter, Δp is the price differential between import and export prices, $E_{e,annual}$ is the exports for year m that are available and used to charge the battery system, and r_d and r_i are the discount rate (which accounts for the inflation rate) and the rate of electricity price increase respectively. It should be noted that the battery model used here is 'realistic', insofar as it aims to take into account realistic battery efficiencies as reported in manufacturer data sheets, as well as empirical data. This results in an average round-trip efficiency of 53.0% for the specific battery and purposes considered here [9]. As this is a relatively low value, certainly compared to efficiencies generally stated by manufacturers, the case of a lossless battery, and a lithium battery with manufacturer reported efficiency, will therefore also be considered in the results. The results for these cases will therefore be independent of the battery model used here.

III. Results and discussion

A. *Benefit of time-of-use pricing*

Fig. 3 shows the benefits of time-of-use pricing compared to the flat rate tariff for the 15 dwellings of the PV group. The benefits are shown for the three types of time-of-use pricing as box plots: the line dividing the box indicates the median, the edges of the box shows the 25th and 75th percentiles, and the 'whiskers' extend to encompass all data, apart from outliers which are indicated by crosses. The results show that none of the PV group would benefit from Economy 7, approximately 50% would benefit from the time-of-use tariff A, and approximately 25% would benefit from the time-of-use tariff D. The range of benefits is small for time-of-use tariff A (£15-20/year), and larger for Economy 7 and time-of-use tariff D (£50-60/year). It would appear that the range of benefits is proportional to the peak to off-peak price range. Overall, it can be said that the PV group would not benefit from time-of-use pricing, with median losses of between £0/year and £35/year.

Referring back to Fig. 2, the 'DFT+PV' and 'DFT' groups indicate the energy-ratios of the PV group with and without PV systems. The DFT+PV group can be seen to lie close to the breakeven line for time-of-use tariff A, and slightly above the line for time-of-use tariff D, confirming the results shown in Fig. 3. The DFT+PV group is shifted to the left and slightly down from the DFT group, which confirms the intuition stated previously regarding how PV would affect energy-ratios. It can be said therefore that for time-of-use tariffs where the day period price is similar to or smaller than the flat price, such as with the Irish tariffs, PV has little to no effect on whether a consumer would benefit from time-of-use pricing. Another way of saying this is that if a consumer benefits from time-of-use pricing without PV then they also benefit from time-of-use pricing with PV, and likewise, if they do not benefit from time-of-use without PV, then they do not benefit from time-of-use with PV.

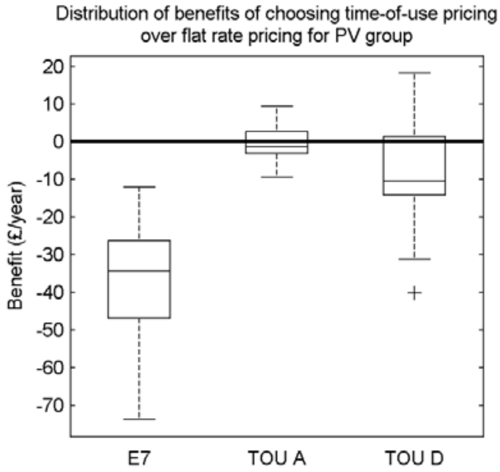

Figure 3. Distribution of benefits of time-of-use pricing compared to flat rate tariff for the PV group.

The situation is different for tariffs like Economy 7, where the day period price is considerably higher than the flat rate price. For these tariffs, PV does make a considerable contribution, insofar as it shifts consumers perpendicular to the breakeven line, and in the correct direction. This can be compared to the case for the Irish tariffs, where PV shifts consumers parallel to the breakeven line. As can be seen in Fig. 3, however, this contribution is still not enough to shift the DFT group past the breakeven line. It would seem reasonable that the same could be said for most UK and Irish consumers (without electric space and water heating), given that the DFT group already has more favourable energy-ratios than the UK flat and IRL control groups, and these are representative of average UK and Irish consumers respectively.

B. *Benefit of battery storage with PV and time-of-use pricing*

Fig. 4 shows the benefits over a year of 430 Ah battery storage systems to the PV group given the three types of time-of-use pricing. The benefits are small, and range from around £5/year to just over £35/year. Benefits are higher for tariffs with higher peak prices, which is to be expected. The median benefit ranges from ~£12/year to ~£20/year.

While these benefits are small, they are larger than the equivalent benefits under flat rate tariffs. Fig. 5 shows the difference in benefits of the battery with time-of-use pricing compared to the benefits of the battery with flat rate tariffs. The results show that choosing time-of-use pricing can have an additional benefit of between £0/year and £20/year compared to choosing flat rate tariff for the systems and tariffs considered here.

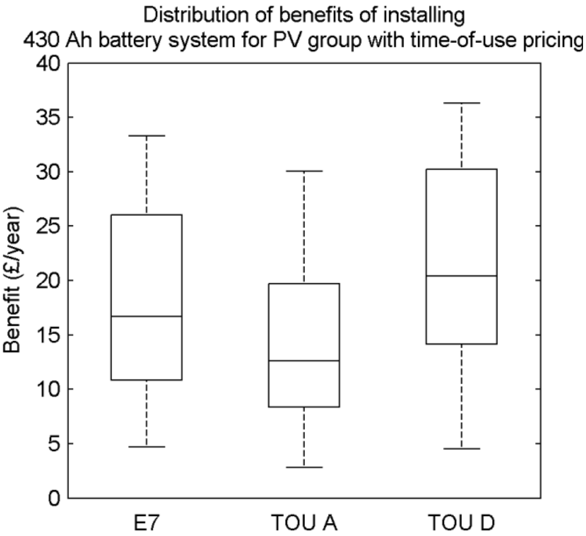

Figure 4. Benefits of battery storage for PV group with three types of time-of-use pricing.

C. *Financial viability of battery storage in domestic PV systems*

Fig. 6 shows target upfront costs for three cases of battery storage system. Consider first the case for the lossless battery (full black circles). This shows target system costs as a function of electricity that was previously exported prior to the installation of the battery, but which is now used to charge the battery. Exports for a 4 kW_{peak} system are shown for reference on the figure, calculated using a yield of 800 kWh/kW_{peak} and exports of 50% of generation. This case uses a battery system efficiency of 100%, a system lifetime of 20 years and an arbitrary price differential between import price and export price of 10 p/kWh. The rate of electricity price increases and discount rate are taken to be equivalent for this case. For the 4 kW_{peak} reference PV system, this gives a target upfront system cost of ~£3250.

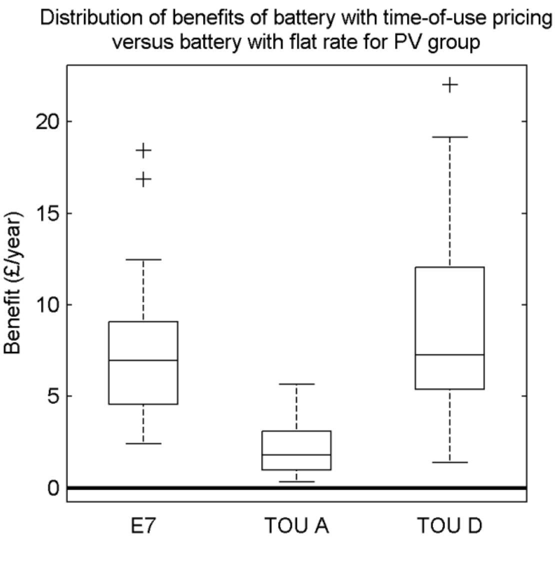

Figure 5. Difference in benefits of battery with time-of-use pricing compared to benefits of battery with flat rate tariff for PV group.

The target costs given the lossless battery can then be used as a basis for deriving more realistic, practical examples. For example, consider the case for the realistic lead-acid battery modelled in this paper, given UK feed-in tariff, shown by filled black triangles in Fig. 6. The system efficiency is 53.0%, the price differential is 11.8 p/kWh – 3.2 p/kWh = 8.6 p/kWh. The system lifetime is assumed to be 20 years, the same as the lossless battery, which is optimistic. The target system cost for the 4 kW_{peak} reference PV system is:

$$£3250 \times \frac{8.6\ \text{p/kWh}}{10\ \text{p/kWh}} \times \frac{53\%}{100\%} = £1481$$

This target can be compared to a commercially available 24 kWh lead-acid battery storage system with battery controller at €6300 (≈£5424) which also has a lifetime estimate of 20 years [8].

Lithium battery systems are another option, and have better efficiencies than lead-acid based systems. Consider therefore a commercially available 8 kWh storage at €13,900≈£11968 [8]. With a German feed-in tariff the price differential is 8c€/kWh ≈ 6.89 p/kWh [9]. Taking the manufacturer stated efficiencies of 96% for battery inverter, and 95% for the battery itself, this gives a target upfront system cost for the 4 kW_{peak} reference case of:

$$£3250 \times \frac{6.89\ \text{p/kWh}}{10\ \text{p/kWh}} \times \frac{96\%^2 \times 95\%}{100\%} = £\ 1961$$

These cases have assumed electricity price increases are equal to the discount rate. If prices increase at a higher rate than discount rates then the target upfront costs will be higher than the values shown above. To take this into account, an approximation can be applied as follows. If electricity price increases are taken to be 2% higher than the discount rate then the upfront costs given above can be increased by approximately 12%. If price increase rates are taken to be 4% higher than discount rates, then the values can be increased by approximately 25%.

Applying the 25% increase to the lossless battery case gives a target cost of £4063 for the 4 kW_{peak} reference PV system. This is 33.5% lower than the cost of the lead-acid system quoted previously, and 195% lower than the cost of the lithium ion system. In order for batteries to be financially viable for domestic PV systems, these differences will need to be closed through reductions in costs, increases in the price differential, or both. Furthermore, as these values are based on optimistic assumptions, such as lossless batteries, in reality the challenge for commercialising batteries in domestic PV applications is likely to be considerably greater.

Note that this study has only considered the specific commercial opportunity to the domestic consumer of using batteries to trade exported electricity for imported electricity. Maintenance and installation costs have not been considered. Furthermore, the authors note that there may be additional benefits to the consumer associated with battery systems, such as backup power supply during power outages, and indeed benefits to other stakeholders, such as distribution network operators concerned with high penetrations of PV on the low voltage network. Consideration of these further benefits falls outside the scope of this paper, and is left for future research.

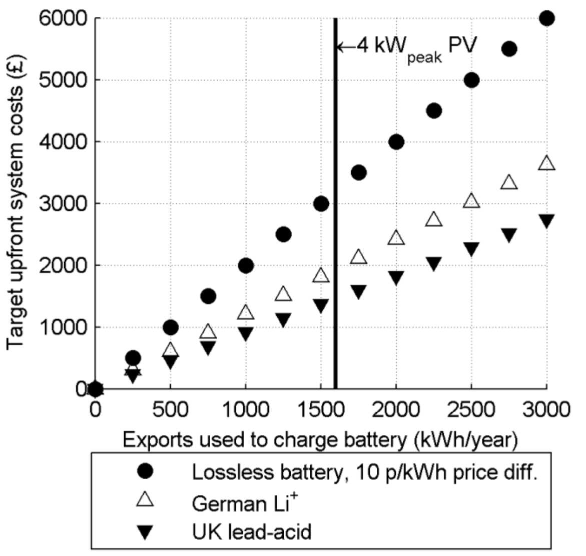

Figure 6. Target upfront system costs for lossless battery with 20 years operation and two practical examples.

IV. Conclusions

This paper has investigated the financial benefit of time-of-use pricing and battery storage systems for domestic consumers with grid-connected PV systems in the UK using data from real dwellings with PV and a realistic battery model.

Three types of time-of-use pricing were analysed: Economy 7, and two tariffs from the Irish Smart Meter Customer Behaviour Trials. It was found that, on average, the group of consumers with PV would not benefit from switching to this time-of-use pricing, with median losses of between £0/year and £35/year. This is due to the fact that the Irish tariffs have day period prices that are similar to the flat rate price, while the benefits of PV with Economy 7 are too low to make Economy 7 financially beneficial.

The benefits of installing a 430 Ah (20.64 kWh) battery system were also small, with median benefits ranging from ~£12/year to ~£20/year, with higher benefits associated with tariffs with higher peak period prices. These benefits are nonetheless greater than equivalent benefits of battery systems with flat rate tariffs.

A method for calculating target upfront system costs for battery systems was presented which yielded target costs for of £4063 for a 'reference case' 4 kW_{peak} PV system with price differential between import and export prices of 10 p/kWh and which assumes lossless batteries and electricity price increases that are 4% greater than the discount rate. This is 33.5% lower than commercially available lead-acid battery systems, and 195% lower than commercially available lithium ion systems, which leads to the conclusion that battery systems are not currently financially viable for domestic PV systems.

Acknowledgments

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