Storage Coordination and Peak-Shaving Operation in Urban Areas with High Renewable Penetration

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***Abstract*—As renewable power generation gains importance, balancing of power demand and supply becomes more and more challenging. This paper addresses this challenge by exploring the potential of individually-owned storage units in decentralised power systems with a high share of renewables. The focus is on the influence of coordination and peak-shaving operation of these individual units in realistic urban areas. Currently extensive amount of research exits on specific applications related to storage coordination. However, in these studies often simplified consumer models are used. This study considers a representative mixed residential and commercial neighbourhood in Amsterdam. The influence of storage coordination and peak-shaving operation on the neighbourhood's energy autonomy and on the peakiness of the power exchanged with the main grid are addressed. Results show that, compared to individual storage operation, coordinated storage operation increases renewable energy utilisation by 39%, decreases the excess energy transferred to the grid by almost threefold and increases the neighbourhood self-sufficiency by 21%. Peak-shaving operation reduces the highest power peak of the year by 55%. These results are statistically significant (p-value $< 10^{-4}$). Thus, in realistic urban areas storage coordination improves local energy autonomy, while peak-shaving operation reduces peaks in power flows exchanged with the main grid.**

I. Introduction

Renewable resources gain importance in power generation. Their output is variable and non-dispatchable, making balancing of power supply and demand increasingly a challenge. This paper addresses this challenge by exploring the potential of individually-owned batteries, such as in electrical vehicles. The impact of coordination and peak-shaving operation of individual units in decentralised urban power systems with a high penetration of renewables is addressed.

Although considerable amount of literature on storage coordination and operation already exists, very few studies focus on the context of real urban environments with mixed residential, commercial and/or industrial customers. Most studies adhere a simplified demand-side view with only a single type of customers, often households (*e.g.*, [1], [2], [3], [4]), although a few (*e.g.*, [5]) target commercial users. The primary focus of most existing modelling studies is not storage integration in realistic environments, but specific technical and economical applications, such as voltage management (*e.g.*, [1], [2], [5], [6], [7]) and local energy cost minimisation (*e.g.*, [3], [4]).

The question how coordination and operation of individual units influences local renewable energy utilisation metrics in real urban neighbourhoods remains largely unanswered. This paper addresses this question by comparing individual and coordinated use of individually-owned batteries such as in electrical vehicles or small stand-alone units. The paper further studies how the algorithm type employed by these storage units influences the peakiness of the power exchanged with the main grid, comparing the performance of a greedy and a peak-shaving algorithm. The focus is on urban environments with mixed household and commercial customers. Industry is left out of scope as it is typically located outside of urban centres. Only solar panels are included as renewable power resources, since wind turbines are less suitable for dense urban areas. A mixed urban area in the centre of Amsterdam, the Netherlands (Fig. 1 left) is chosen as case study.

This paper seeks to contribute to the development and real-world emergence of (semi-)autonomous local energy communities. Increasing importance of renewables for power generation is expected to drive the transition from the current centralised to a future decentralised power system. This future system can be seen as an interconnected *smart grid* consisting of local *microgrids* [8], [9]. The core concept of the smart grid is its bidirectional information exchange capability [10], [11]. Microgrids are often defined through their ability to decouple ("island") from the main grid during contingencies, becoming autonomous portions of the grid (*e.g.*, [12], [13]). This paper considers microgrids during normal operation, *i.e.* while they remain connected to the main grid. Their ability to internally balance demand and generation on a neighbourhood-level scale by taking over local grid operation and control tasks is key. In particular, microgrids can coordinate and operate individually-owned batteries in the neighbourhood.

The aim of this paper is to study how coordination and operation of individually-owned batteries influences (1) local energy autonomy and (2) microgrid behaviour towards the main grid. Local energy autonomy is defined as a high degree of *self-sufficiency* (demand is satisfied by local generation) and *self-consumption* (locally generated power is used by own demand). Microgrid behaviour towards the main grid is addressed as the microgrid ability to avoid peaks in power flows exchanged with the main grid. Such peaks are both costly to manage during grid operation as well as costly to account for during grid design [15]. In the past, power flow peaks occurred solely due to demand surges. Renewable generation also causes power flow peaks, exacerbating their

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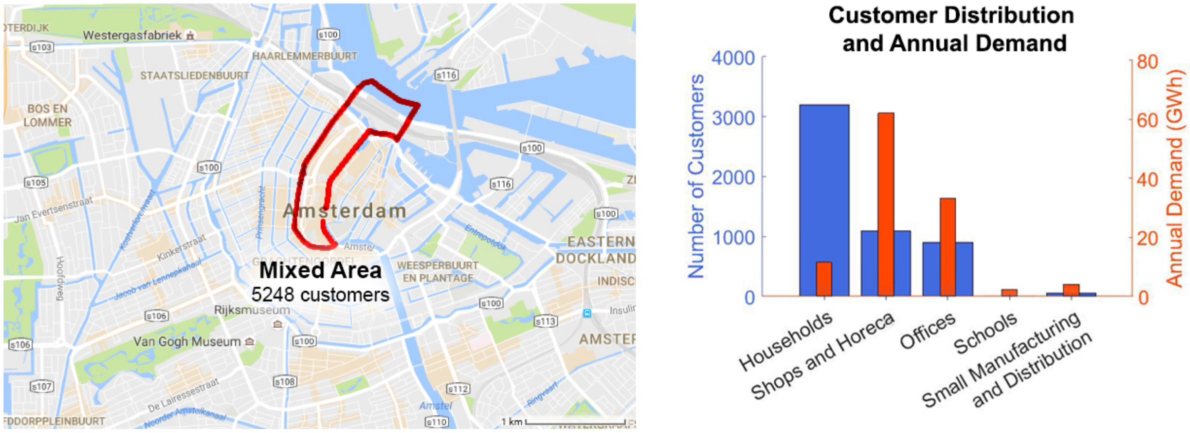

Fig. 1: Geographical location (left) and customer distribution and annual demand (right) of the selected representative mixed urban neighbourhood in Amsterdam, the Netherlands [14].

occurrence in the power system. The peak-shaving potential of storage as addressed in this paper, can help decrease grid operation costs and grid reinforcement investments.

The main contributions of this paper are the following:

1) Modelling of a realistic urban environment with mixed residential and commercial consumers.
2) A quantitative assessment of the increase in local energy utilisation with coordinated operation of individually-owned batteries, as compared to individual operation.
3) A quantitative assessment of the decrease in peak power flows if a peak-shaving charging/discharging algorithm is used, as compared to a greedy algorithm.

The remainder of this paper is organised as follows. Section II describes the used storage coordination assumptions, the charging/discharging algorithms, the metrics considered, and the data used in model development. In Section III the modelling results are presented. Section IV discusses these results. Conclusion and an overview of future work are given in Section V.

II. Methods

This paper studies (1) the influence of individual and coordinated operation of individually-owned batteries on local renewable energy utilisation, and (2) the influence of greedy and a peak-shaving battery operation on power flow peak occurrence. A realistic model of a mixed urban area with households and commercial customers is presented. The number and annual demand of the considered customers are shown on Fig. 1 (right). It is assumed that 50% of the customers have solar photovoltaic (PV) panels and 50% have batteries.

A. Individual versus Coordinated Operation

The first research question addressed in this paper concerns the influence of storage coordination. Two scenarios are compared: individual and coordinated operation of individually-owned storage and PV units. In case of individual operation, each PV and/or storage owner uses only the individual capacity of her own installation. Excess or shortage of power is exchanged with the main grid. In the coordinated case, all PV and storage capacities of the microgrid are pooled together and used jointly. Residual power excesses or shortages are exchanged with the main grid.

B. Naive versus Peak-Shaving Algorithms

The second research question deals with the influence of the charging/discharging algorithm on the behaviour of the microgrid towards the main grid. Two algorithms are compared: a *greedy* and a *peak-shaving* algorithm. Both schedule charging and discharging in discrete timesteps (here: one hour).

At the beginning of timestep t, the *greedy* algorithm takes into account the (forecast) load and renewable generation of timestep t, as well as the current state of charge (SoC) of the battery. If any generation excess occurs, it is stored entirely, to the degree that storage capacity is available. Similarly, if any generation shortage occurs, demand is met entirely, or until all stored energy is used.

Contrarily, at the beginning of timestep t, the *peak-shaving* algorithm takes into account the (forecast) load and renewable generation of timesteps t through $t{+}h$ (with h the forecastable time horizon, here $h = 5$), as well as the current SoC of the battery. Assume there is a generation excess (*i.e.* positive mismatch) in each of the timesteps up to $t + h$. The peak-shaving algorithm first sorts these mismatches according to their magnitude. Next, storage capacity is reserved for the *difference* between the largest and the second largest mismatch. This is repeated for all subsequent differences, until all differences (*i.e.* all excess) is stored or until no remaining storage capacity is available. A similar procedure is followed when demand exceeds generation. When mixed mismatches occur in the forecast period, only the subsequent mismatches with the same sign as the mismatch of timestep t are taken into account.

The use of the peak-shaving algorithm enables the adaptation of charging and discharging schedules to forecast demand, generation and SoC such that, given enough storage capacity is available, all foreseeable excess is stored or demand is met,

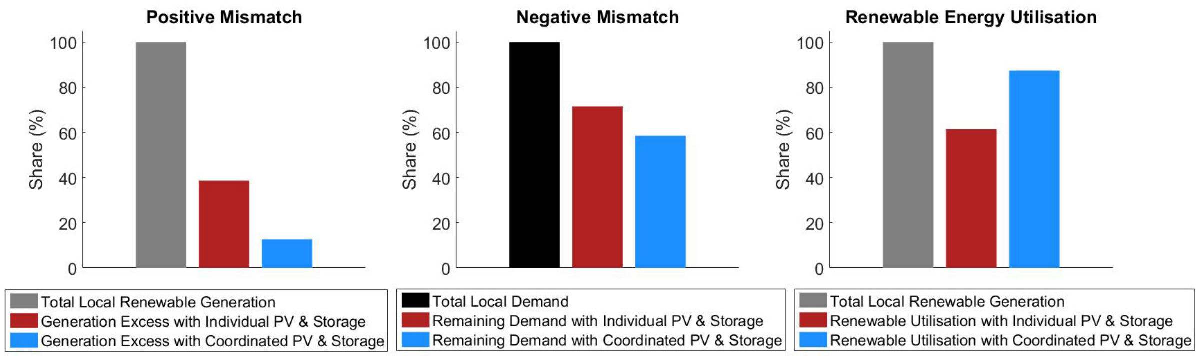

Fig. 2: Comparison of cumulative annual metrics for individual and coordinated storage operation. Results are shown relative to the total annual microgrid renewable generation (for positive mismatch and renewable energy utilisation) and total annual demand (for negative mismatch).

while peaks in generation and load excess power flows are limited. The algorithm assumes increasing forecast uncertainty, from 5% for the current timestep t to 20% for $t+h$ [16], [17].

C. Metrics

The performance of storage operation and implemented algorithm is assessed by four metrics. First three metrics reflect local energy autonomy. The last metric relates to the behaviour of the microgrid towards the main grid.

- **Positive Mismatch.** Generation excess transferred to the main grid.
- **Negative Mismatch.** Remaining demand supplied by the main grid.
- **Renewable Energy Utilisation.** Share of renewable energy which is utilised locally. Renewable energy utilisation for each time step is calculated as the sum of direct consumption and energy stored.
- **Power Flow Peaks.** Maxima in power flow due to either high net generation or high net demand.

D. Data and Assumptions

The case study neighbourhood in this paper is selected from the neighbourhoods defined by Statistics Netherlands [14] and is assumed to be a representative mixed urban area. Detailed measured consumption data for urban areas are scarce. This is also the case for the selected area. Therefore the simulation model developed in this study combines three databases to estimate hourly power consumption in the selected mixed area:

1) The number of households and different commercial customers types in the mixed area in the centre of Amsterdam [14]. This is measured data.
2) Measured hourly profiles of 61 households elsewhere in the Netherlands for the period between May 1st, 2012 and April 30th, 2013.
3) Modelled hourly commercial consumption profiles. These data are based on the United States Department of Energy commercial reference models [18], [19], adapted for the Dutch context as described in [20] for the same period as the household data.

Based on the number of customers of each type (dataset 1), the corresponding number of household (dataset 2) and commercial (dataset 3) profiles are matched to the considered area. The result is a realistic mixed microgrid consumption profile. This approach is validated by calculating the annual cumulative consumption simulated by the model and comparing this to the measured annual cumulative consumption as reported in [21]. The deviation between the modelled and the measured cumulative annual consumption is 16%.

Renewable power in this model is assumed to be generated by PV. Their output is modelled using weather data [22] for the same period and the same location as the demand profiles. Insolation data are converted into power generation data using the model developed by Walker [23] and technical specifications of the Solarex MSX-60 panels [24]. Storage is modelled as lithium-ion batteries with battery-to-grid and grid-to-battery efficiencies of each 90%. The model assumes a 50% penetration of both PV and storage. However, PV and storage owners do not necessarily overlap, although the model errs on the conservative side by assuming that PV owners have a higher probability of having their own storage. PV and storage units are assigned at random at each model run. Both PV and storage unit capacity are proportional to the owners' annual power consumption (PV size of 1 kW_p per MWh annual consumption and battery size of 1 kWh per MWh [25], [26]).

The results presented are obtained from 25 simulation runs. Differences between the runs lie in variations in the ownership of PV and storage. Results from the simulations are analysed using non-parametric tests as underlying values are found not to be normally distributed.

III. Results

This section presents the results of a case study in a realistic mixed urban area in the centre of Amsterdam. Two research questions are addressed: (1) what is the influence of individual versus coordinated operation of individually-owned storage units, and (2) what is the influence of the charging/discharging algorithm employed by these storage units?

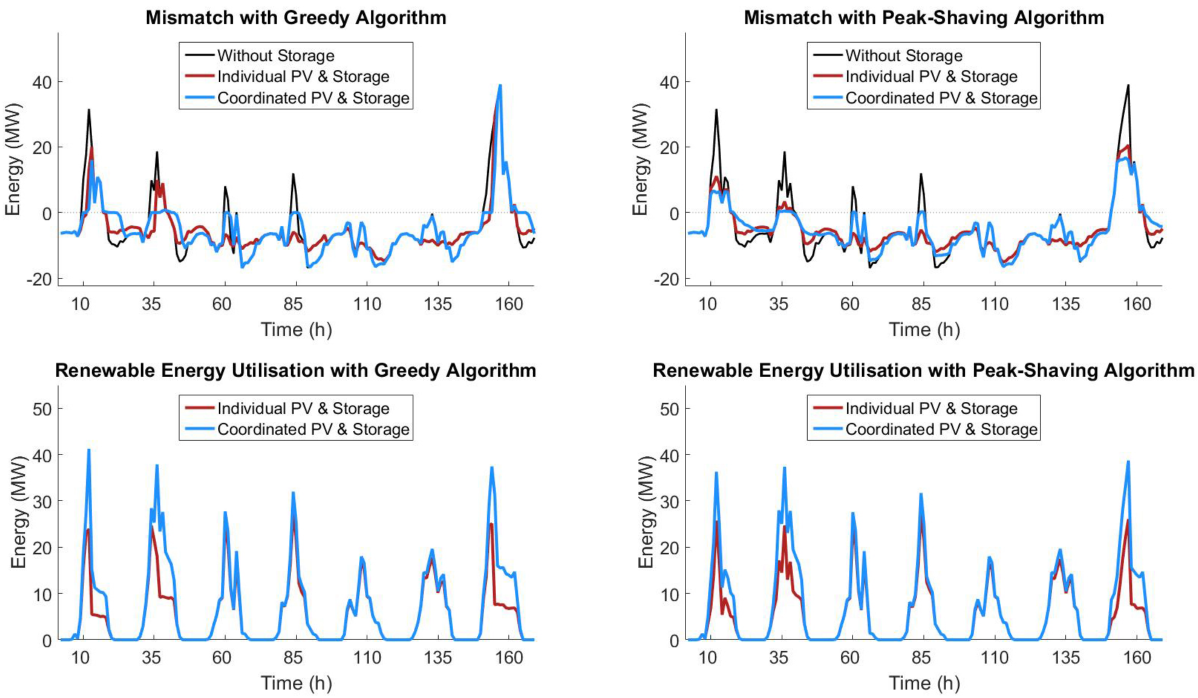

Fig. 3: Comparison of mismatches (*i.e.* power exchanges with the grid) and renewable energy utilisation metrics for greedy (left panels) and peak-shaving (right panels) algorithms. In both cases individual and coordinated storage operation are compared. Additionally, original mismatch (*i.e.* without storage) is shown on the top panels. The period shown is May 7th - 13th, 2012. The peak at hour 156 is the highest power peak of the modelled year (May 1st, 2012 - April 30th, 2013).

A. Individual versus Coordinated Operation

In this paper, storage is assumed to consist of individual units at the consumers' premises. Two scenarios are compared: individual and coordinated operation of these units. Fig. 2 shows cumulative annual results for three metrics: positive mismatch (energy excess, transferred to the main grid), negative mismatch (energy shortage, supplied from the main grid) and renewable energy utilisation. The results presented are relative to the total local renewable generation (for positive mismatch and renewable energy utilisation) and to the total annual load (for negative mismatch).

With individual storage operation, 38% of the generated renewable energy is transported to the main grid, while 62% is used locally. With coordinated operation, only 14% is transported to the main grid, *i.e.* 86% is used locally. This represents a relative increase of 39% in self-consumption. Increase in self-consumption also results in an almost threefold decrease of energy excess which is transferred to the main grid. Further, with individual storage operation, 69% of the annual microgrid demand needs to be satisfied by the main grid, compared to 57% with coordinated storage. This is a relative increase of 21% in self-sufficiency.

The statistical significance of these results is assessed using the Wilcoxon signed-rank test. For each of the three considered metrics, the sets of individual and coordinated storage operation results from 25 runs are compared. Thus, three comparisons of 25 value pairs are made. Each of the three comparisons yielded a p-value of $1.23 * 10^{-5}$, from which can be concluded that the above described differences between individual and coordinated storage operation are statistically significant. Thus, for all three metrics, storage coordination significantly outperforms individual storage operation.

B. Naive versus Peak-Shaving Algorithm

The second research question addressed in this paper is the influence of the charging/discharging algorithm on the behaviour of the microgrid towards the remainder of the grid. Fig. 3 shows mismatches (*i.e.* power exchanges with the grid) and renewable energy utilisation for a period of seven days (May 7th - 13th, 2012). Left panels represent results obtained with the greedy algorithm and right panels those obtained with the peak-shaving algorithm. Both are applied to individual as well as to coordinated storage operation. For reference, original mismatches (*i.e.* without storage) are also shown on the upper panels. Note that each upward peak represents daytime (solar generation), while the valleys in between are nighttimes.

On the last day shown in Fig. 3 the largest power peak (43 MW) of the modelled year occurs (at $t = 156$). With the greedy algorithm, either with individual or coordinated storage operation, the residual peak equals the original peak. With the peak-shaving algorithm the height of the peak decreases to 23 MW with individual storage operation, and to 18 MW with coordinated storage operation. Note that with the greedy algorithm, mismatch is zero for the first three hours of high solar generation ($t = [151, 153]$). At that point, all available storage capacity is used and excess renewable energy is transferred to the main grid (*i.e.* residual mismatch follows original mismatch). With the peak-shaving algorithm, storage is not used at the onset of the peak, thus initially mismatch follows the original mismatch, leaving storage capacity available to store energy during the highest generation hours ($t = [152, 156]$). Note further that, for the same period, the increase in renewable energy utilisation is less steep for the peak-shaving algorithm than for the greedy algorithm. Recall that renewable energy utilisation at timestep t is defined as the sum of direct utilisation and energy stored during that timestep. Since demand is independent of the charging/discharging algorithm, the difference in renewable energy utilisation can be attributed to the different use of storage by the two algorithms.

Finally, the use of the peak-shaving algorithm does not always result in a decrease of demand peaks (*e.g.*, at $t = 112$). The largest demand peak of the year is 22 MW, irrespective of storage operation or algorithm. This peak occurs on January 6$^{\text{th}}$, 2013 (not shown on Fig. 3). This winter demand peak is approximately half of the highest generation peak in the modelled system (43 MW). The inability of the peak-shaving algorithm to reduce demand peaks can be attributed to the insufficient local generation capacity to meet all microgrid demand (annually only 31% to 43% of the microgrid demand is supplied by local generation, see Fig. 2). This is in particular the case in periods of low solar power generation (such as in the hours preceding $t = 112$ on Fig. 3).

To test the statistical significance of the differences in mismatches between the greedy and the peak-shaving algorithms the Wilcoxon signed-rank test is used for both individual and coordinated storage operation. For each hour of the year, the mismatch values obtained after application of the greedy algorithm in 25 simulation runs are compared to the corresponding values obtained with the peak-shaving algorithm. Statistically significant differences between the two algorithms are found for both individual and coordinated storage operation. For example, the p-values for the difference between the two algorithms for both individual and coordinated storage operation are $1.23 * 10^{-5}$ at both $t = 11$ and $t = 156$. Thus, the peak-shaving algorithm significantly outperforms the greedy algorithm, irrespective of storage coordination.

IV. Discussion

This paper shows significant benefits of coordination and peak-shaving operation of individually-owned storage units in a realistic mixed urban area. Storage coordination improves local energy autonomy and renewable energy utilisation, and is thus advantageous for local prosumers. Peak-shaving algorithm implementation is of particular importance to the distribution system operator (DSO) as it governs the occurrence of peak power flows, which in their turn determine grid operation and investment costs.

Currently battery penetration in urban power grids is low, however this is expected to change as costs drop [4]. Nevertheless it remains unclear how local storage will be organised in future high-renewables decentralised power systems. In the literature two main perspectives on storage organisation exist: neighbourhood-level storage either consists of centrally located MW-scale batteries (*e.g.*, at a substation), or it is the collection of distributed smaller-scale units along the feeders, which are networked together [6]. This paper adheres to the latter view, although the results obtained for coordinated storage are also applicable to the MW-scale battery approach.

Coordination of individually-owned storage units is an important advantage for local energy autonomy. In a microgrid context, coordinated operation can be achieved both through central and decentralised control, assuming bidirectional communication channels are in place. A microgrid is expected to have a microgrid central controller (MCC) that acts as an interface for the DSO and/or other responsible third party. Each controllable unit in the microgrid, including storage units, has a local controller (LC). In a centralised operation each LC receives setpoints from the MCC. In a decentralised operation, LCs have a more advanced degree of intelligence and make decisions locally [13], [27]. However, in addition to the technical ability to coordinate individually-owned storage units, also incentive mechanisms inciting owners to allow coordination are needed.

Despite increasing penetration of renewables and expected similar trends for storage, it is likely that not all individuals within a microgrid will own PV and/or storage units. In this study the penetration of PV and storage is assumed to be 50%. Thus, generation and storage capacities are expected to be shared between microgrid members. Their mutual use therefore requires adequate remuneration schemes. For instance, as batteries only have a limited number of charge cycles [7], community use of individually-owned units is only economically viable if lifetime reduction due to community use is offset by payments to the storage owner. Thus, successful deployment of storage coordination requires both the right control as well as the right incentive scheme.

Similarly, implementation of the peak-shaving operation of individually-owned units will require adequate remuneration from the DSO or another grid responsible third party. This study compares a greedy and a peak-shaving algorithm. Cumulative annual metrics such as positive and negative mismatch, and renewable energy utilisation are equal for both of these algorithms. However, the algorithm type does influence the timing of power exchanges with the grid, and thus the occurrence of peak power flows. Therefore, the use of the peak-shaving algorithm is primarily of importance to the DSO. Reducing peak power flows can for instance lead to deferral or avoidance of grid reinforcement investments. While the incentive scheme for coordination of local storage units is expected to be based on mutual payments between microgrid members, is the remuneration mechanism for peak-shaving based on DSO payments to storage owners. A similar case is addressed by Sugihara *et al.* [5], who propose an initial subsidy for individual storage purchase paid by the DSO to (commercial) consumers in exchange for partial control of their storage units. These considerations show that implementation of both storage coordination and peak-shaving operation in real urban power systems require a multi-disciplinary approach to succeed.

V. Conclusion and Future Work

This paper focuses on the context of future urban power systems with a high penetration of distributed renewable generation resources and assesses the impact of coordination and operation of decentralised storage. The realistic urban focus is a first contribution of this paper. The second contribution is the quantitative comparison between individual and coordinated operation of individually-owned storage units on local energy autonomy. The third contribution is the quantitative comparison between a greedy and a peak-shaving algorithm implementation on the behaviour of the microgrid towards the main grid. The results obtained show considerable and statistically significant benefits of both coordinated storage operation as well as of the use of a peak-shaving algorithm.

This paper thus seeks to contribute to the development and deployment of decentralised power systems in real urban environments. However, a number of issues remain to be addressed, including the development of technical control approaches, communication protocols and adequate remuneration schemes to incentivise storage coordination and peak-shaving operation. As shown in this paper, storage coordination and peak-shaving operation is beneficial for, respectively, the microgrid prosumers and the DSO. However, as long as control, communication and remuneration agreements do not exist, implementation of these results in reality is unlikely.

Although considerable work for future research remains, current results show promising prospects of storage coordination and peak-shaving operation in real urban environments.

Acknowledgements

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