THE CASE FOR COORDINATED ENERGY STORAGE IN FUTURE DISTRIBUTION GRIDS

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ABSTRACT

The integration of distributed renewable energy sources in urban power systems requires locally tailored approaches. This paper studies the impact of storage penetration and its coordination in three representative urban areas in Amsterdam: a residential, a business and a mixed area. Results show considerable benefits of storage and its coordination in all three areas, assuming a high (50%) penetration of solar panels. Self-consumption of locally generated renewable energy increases from 70% without storage to 80% with individually used storage and to over 90% with coordinated storage. Self-sufficiency increases from 17% without storage to almost 40% with coordinated storage. These results make a case for coordinated use of storage units to support the integration of renewable resources in future distribution grids in a variety of urban areas.

INTRODUCTION

Storage is considered a promising approach to facilitate balancing of power demand and supply in grids with increasing penetration of renewables [1], [2]. This paper focuses on battery-type storage. Batteries are particularly suited for *local* power balancing as they are relatively small compared to other storage technologies. The design and operation of battery capacity therefore depends on local balancing needs, which are dictated by variations in local generation and demand. In an urban context, demand varies at much smaller scale, between buildings and neighbourhoods, than generation [3]. To adequately design and use storage, it is therefore key to understand how local differences in urban demand influence the local need for and the impact of storage. These topics have thus far received little attention in literature. This paper addresses this hiatus by studying the impact of storage in three representative urban areas: a residential, a business and a mixed area.

Urban energy demand is growing due to increasing electrification and urbanisation. The need to satisfy this growing demand while curbing emissions calls for a wide-spread adoption of renewables in urban power systems [4], [5]. As these resources are typically connected to the distribution grid, their rise presents unprecedented challenges for distribution system operators (DSOs). Local power demand and supply balancing is expected to become one of the new distribution grid tasks. Batteries can be used to fulfil this task. However, currently little literature exists on the effects of local storage at neighbourhood scale. Most literature focuses either on optimisation of individual systems (e.g. [6], [7]), or on long-term country-level outlooks (e.g. [8]). Limited work has been done on an intermediate level. Moreover, only a few authors studied the coordination of individual storage systems, thereby considering solely residential consumption (e.g. [9], [10]). Real urban power demand is typically a mix of residential and business consumption. In this work the impact of storage on the integration of renewables is studied for three representative urban areas. Specifically, two aspects of storage are addressed: (1) increasing penetration of individually-owned batteries, and (2) the influence of their coordination.

METHODS

This paper uses three urban areas in Amsterdam, the Netherlands as case study: a residential, a business and a mixed area. The focus is on the impact of storage on renewables integration. To study the impact of increasing storage penetration, battery ownership is varied from 0% to 100%. To study the influence of storage coordination, individual and coordinated use of batteries are compared.

Modelling Local Power Demand

Local power demand is modelled on neighbourhood level. The neighbourhoods used are defined by Statistcs Netherlands [11] and are assumed to be representative for different types of urban areas. The geographical location of the selected areas is shown in Fig. 1, their consumer distribution and demand is shown in Fig.2. Key parameters of the selected areas are summarised in Table 1.

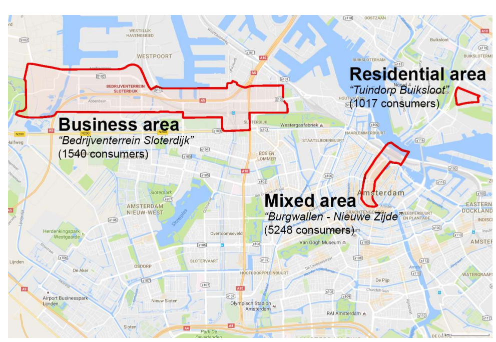

Fig. 1. Location of selected urban areas in Amsterdam.

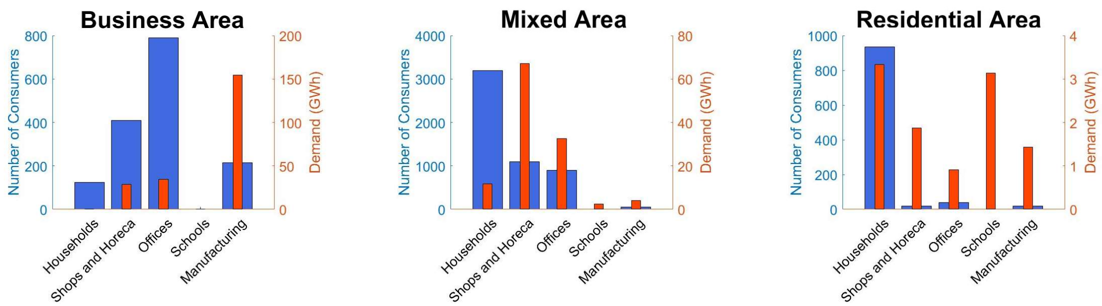

Fig. 2. Number of consumers (blue) and their annual simulated demand per consumer type (orange) for the three selected urban areas.

Measured hourly power demand data are scarce. Yet detailed profiles, with a high granularity in both space and time are required to accurately assess the local impact of renewables and storage. Therefore, in this paper a simulation approach is used, which approximates local power demand by combining two types of data sources:

1) Data on local building use (i.e. residential or business use, and type of business activities).
2) Data series of household and business power demand from similar consumers elsewhere.

This approach is applied here for the three selected areas:

1) The number of households and businesses in each area is obtained from Statistics Netherlands [11].
2a) Household demand is obtained from measured hourly profiles of 61 households elsewhere in the Netherlands for the period between May 1st, 2012 and April 30th, 2013.
2b) Business demand is obtained from modelled hourly commercial consumption profiles. These are based on United Stated Department of Energy commercial reference models [12], [13], adapted for the Dutch context as described in [14] for the same period as the household data.

Based on the number of households and businesses (dataset 1), the corresponding number and type of demand profiles (datasets 2a and 2b) are matched to each of the selected areas. In each area, all individual profiles are summed up to yield an hourly profile for the whole area for the entire considered period. To verify the approach, the annual simulated demand is calculated and compared to the corresponding measured annual data available from [15]. The deviation is less than 20% (see Table 1). This accuracy suffices for the purpose of this paper. Yet, there is room for improvement, which emphasises the need for more detailed measured local demand data.

Renewable Power Generation Assumptions

In this paper, renewable power is assumed to be generated by solar panels on consumers' roofs. A single scenario of renewable resource penetration is used: in all three areas, 50% of the consumers are assumed to have solar panels. For each consumer, the PV system is sized relative to her annual power demand (using 1 kW_p per MWh_a [6], [7]). PV output is modelled using solar insolation data [16] for the same period as the demand profiles. These data are fed into the model developed by Walker [17] using the technical specifications of Solarex MSX-60 panels [18].

Storage Scenarios and Assumptions

The integration of renewables requires new balancing approaches. Here, storage is taken as an example of such an approach. The differences in impact of similar storage integration measures on different urban areas are studied. Two different aspects of storage integration are addressed:

1) Increasing storage penetration (0% - 100%)
2) Individual versus coordinated use of local storage

Increasing storage penetration entails that an increasing share of consumers have a storage unit at their premises. Across all scenarios, storage units are sized relative to the consumer's annual demand (1 kWh per MWh_a [6], [7]). Storage coordination pertains to the accessibility of storage capacity to other members of the neighbourhood. **Individual storage use** assumes that a unit owner can use only her own storage (and PV) capacity. It is assumed that PV-owners have a higher probability of owning storage. **Coordinated storage use** entails that storage (and PV) capacity are used jointly by the entire neighbourhood [19]. In all scenarios storage units are assumed to be lithium-ion batteries with battery-to-grid and grid-to-battery efficiency of 90% each, and thus a round-trip efficiency of 81%.

Table 1. Key parameters of selected urban areas.

Urban Area	Number of Consumers	Share of Households *(%)*	Simulated Demand *(GWh/year)*	Measured Demand *(GWh/year)*	Simulation Deviation *(%)*
Business	1017	8	211	214	2
Mixed	5248	61	114	98	18
Residential	1540	92	10	9	16

Simulations

Each storage penetration scenario is simulated 30 times. Results from the simulation runs differ as in each run, PV and storage units are assigned to consumers at random. Since PV and storage capacity depend on the consumer's annual demand, this assignment changes the total capacity of storage and PV in each run. This approach represents the real uncertainty DSOs face, as consumer decisions to install, for instance, PV it is beyond their control.

Metrics

The impact of storage on local ability to integrate renewables is assessed using the following four metrics:

- **Renewable Energy Utilisation.** Amount of renewable energy which is used locally.
- **Maximal Annual Power Peak.** Highest power flow of the modelled year.
- **Self-consumption.** Share of renewable power which is consumed by local demand.
- **Self-sufficiency.** Share of demand satisfied by local generation.

RESULTS AND DISCUSSION

The impact of increasing storage penetration and of storage coordination is assessed using four metrics in three different representative urban areas in Amsterdam. Two effects are addressed: (1) increasing storage penetration, and (2) individual versus coordinated storage operation. Fig. 3 shows the results.

Renewable Energy Utilisation

Increasing penetration of storage leads to more renewable energy being used locally. This effect is strengthened by coordinated use of storage, as compared to individual use. For **individual operation** of storage, the steepest gain in local renewable energy use is found for storage penetration of up to 60%. This value implies that incentivising storage penetration beyond a capacity of 0.6 kWh per MWh_a is likely to be ineffective, especially without additional approaches (e.g. demand response or generation diversification). It should be noted that the exact value of the turning point depends on the share of consumers with both storage and PV, as storage ownership without access to PV does not yield benefits given individual unit operation.
Local renewable energy utilisation further improves significantly if storage and PV are used in a **coordinated** fashion. The benefits of coordination are already apparent at 0% storage penetration. Coordination then pertains to the use of PV systems only. This increases local renewable energy use by up to 78%, as compared to individual PV use. Storage further improves this value. At 60% storage penetration, renewable energy utilisation nearly doubles as compared to no storage scenario. Similarly to the individual use scenario, the benefits of increasing storage penetration taper off in the coordinated scenario.

Maximal Annual Power Peak

The maximal annual power flow peak is a key metric for sizing of physical components in the distribution grid. Decreasing this peak can result in important cost savings. The peak shaving algorithm used here is described in [19]. Fig. 3 shows that no reduction in maximal peak is obtained without storage (blue lines in second row of Fig. 3, at 0% storage penetration do not yield any peak reduction).
With **individual** use of storage and PV, largest peak reductions are observed for storage penetration of up to 60%. At 60% penetration, the maximal annual power peak is reduced by up to 30%. With **coordinated** storage, the reductions of maximal power peaks are around 40% at 60% storage penetration.

Self-consumption

Self-consumption is relatively high (70%) without storage across all the studied areas. Storage further improves this value. At a penetration of 60%, self-consumption increases to 80% with individual use and up to 95% with coordinated use of storage capacity.

Self-sufficiency

Contrary to self-consumption, self-sufficiency is low (around 17%) without storage. Storage improves this metric. At 60% penetration, self-sufficiency is around 30% if storage and PV are used individually and around 40% if they are used in a coordinated fashion.
The combination of a high self-consumption (close to 100% at high coordinated storage penetration) and corresponding low self-sufficiency indicates that overall, a total area solar panel capacity of 0.5 kW_p per MWh annual consumption is insufficient to supply the power needs of the modelled areas. If further increase in self-sufficiency is desired, additional local generation is required.

Urban Areas Comparison

Availability of storage and its coordinated use improves all studied metrics across all areas. However, the extent of the gains varies between the different areas. Highest average gains are observed for the residential and mixed areas, while lowest benefits are obtained in the business area. This can be attributed to demand profile differences. Business demand peaks during the day, i.e. simultaneously with the peak in solar power generation (PV is the only assumed renewable resource in this paper), while residential demand peaks in the evening. Thus, the baseline for the business area is relatively higher, and therefore the gains due to increasing storage are smaller.
The results shown on Fig. 3 are averages obtained from 30 simulation runs. Results from individual runs vary (not shown on Fig. 3). Relative standard deviations are largest for the residential area (14% to 24% for the four different metrics), and smallest for the business area (1% to 10%). This variability is found for all three storage scenarios.

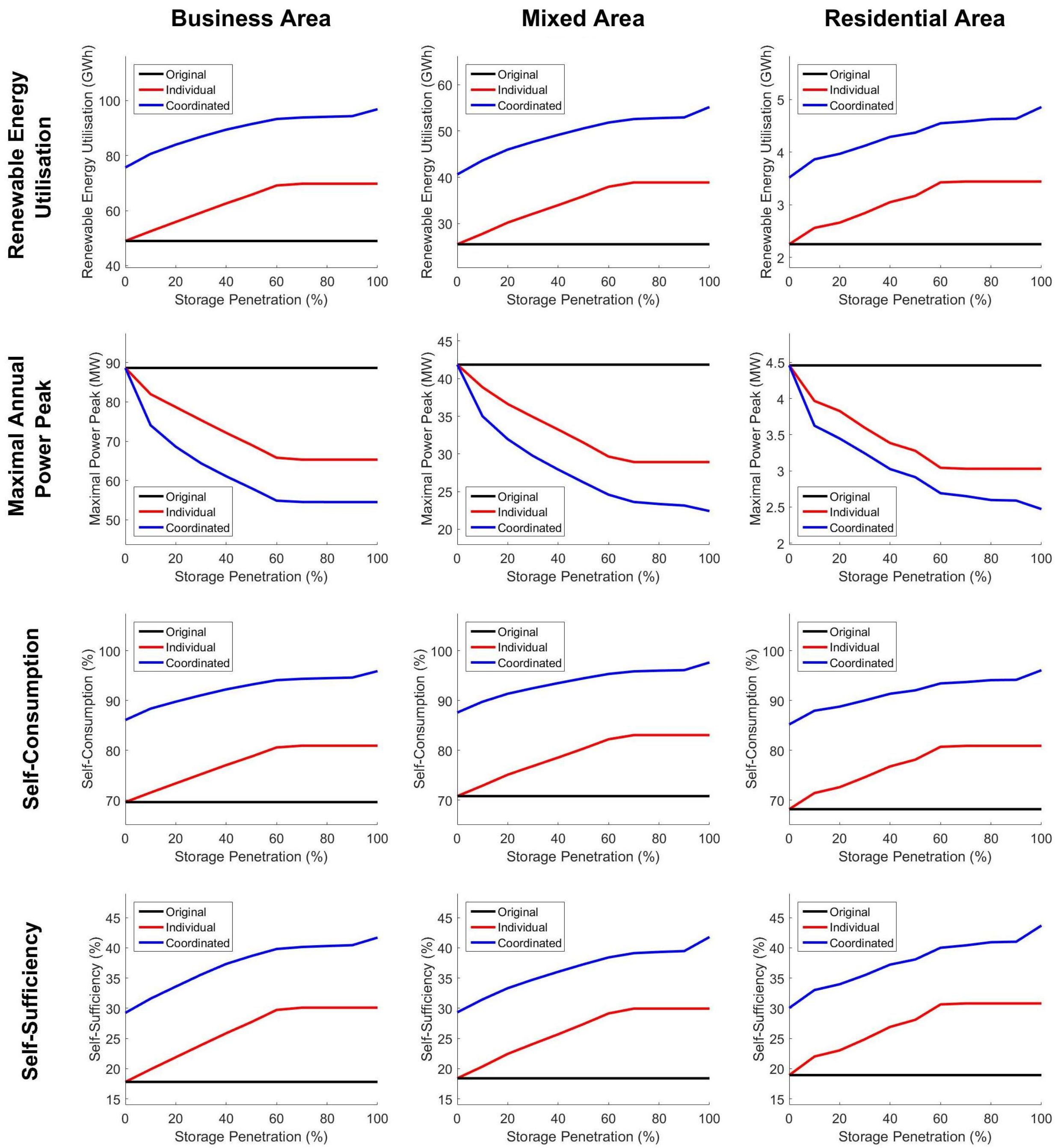

Fig.3. The impact of storage on four metrics assessing the local ability to integrate renewable resources in three representative urban areas. The four metrics are shown in subsequent rows: renewable energy utilisation (upper row), maximal annual power peak (second row), renewable energy self-consumption (third row), and area self-sufficiency (bottom row). The three representative areas are shown in three columns: business area (left), mixed area (centre), and residential area (right). Each subplot shows the impact of increasing storage penetration (from 0% to 100% of consumers having their own storage units) for three scenarios: original scenario (no storage, individual PV), individual scenario (individually used storage and PV) and coordinated scenario (coordinated use of storage and PV). The original scenario is shown as a reference. For all plots and scenarios, the PV penetration is kept constant at 50% of the consumers having their own installation. The noise is attributed to variations in PV and storage sizes, which result from the random assignment and corresponding sizing of PV and storage systems. Note that in each simulation the original, individual and coordinated scenarios are calculated for the same set of PV and storage capacity. The results shown are averages of 30 simulations.

Most of this variability can be attributed to variations in PV size and thus their output. In real power systems, PV system size is typically outside of the control of DSOs. Therefore, the obtained results indicate that the uncertainty in the business area is considerably smaller than in the residential area. Thus, similar measures (e.g. the installation of x kWh storage capacity per MWh annual demand) in a residential neighbourhood *on average* leads to the highest metric gains. However, the actual outcome is more uncertain in a residential than in a business area.

CONCLUSIONS AND FUTURE WORK

This paper shows the benefits of increasing storage penetration and of its coordination across different representative urban areas with a high penetration of renewables. First, results show that increasing storage penetration leads to gains across all studied metrics, although this effect tapers off at penetrations above 60%. Second, this paper presents a quantitative comparison between individual and coordinated use of individually-owned batteries. Results shows significant benefits of coordinated storage operation. Thus, incentivising and facilitating local asset coordination is beneficial both for local consumers and producers (e.g. increased self-consumption and self-sufficiency) as well as for the DSO (e.g. decrease in maximal power flow peaks). DSOs can use these results and the underlying model to (1) predict the effects of increasing renewables penetration in specific areas, including new developments for which no historic data are available, and (2) design tailor-made local measures to facilitate the integration of renewables. This work relies on a simulation approach for areas with scarce demand data. Further improvements of this approach require the availability of detailed measured demand data.

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