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The potential for peak shaving on low voltage distribution networks using electricity storage

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ABSTRACT

Co-location of energy storage with demand provides several benefits over other locations, while still being able to provide balancing services to the grid. One of these additional benefits is deferral of distribution infrastructure reinforcement, allowing increased load growth. This paper considers the potential of electricity storage for peak shaving on distribution networks, focusing on residential areas. A demand model is used to synthesise high resolution domestic load profiles, and these are used within Monte Carlo analysis to determine how much peak shaving could be achieved with storage. An efficient method of finding the potential peak shaving using electricity storage is developed for this purpose. It is shown that moderate levels of storage capacity can deliver significant demand reductions, if suitably coordinated and incentivised. With 2 kWh of battery storage per household, the peak demand at low voltage substations could potentially be halved. The effects of PV capacity, household size and C rates are considered. With 3 kW PV per house, 4.5 kWh of batteries could keep peak flows at the same level as before the addition of PV. It is also shown that 3 kWh of battery storage per household could allow provision of all heating from heat pumps without increasing the peak demand.

1. Introduction

1.1. The benefits of distributed energy storage

To deal with the increasing penetration of variable renewables associated with decarbonisation of the energy system, as well as increasingly simultaneous load from heat pumps and electric vehicle charging, flexibility is becoming increasingly important. There are four main approaches to providing flexibility in a low carbon energy system: flexible generation (such as gas with CCS), interconnection to other countries and regions, demand response (such as smart charging of electric vehicles), and finally energy storage, on which this paper focuses.

Of the many candidate electricity storage technologies, batteries are of particular interest at small- and medium-scales due to their relatively high energy density, lack of geographic constraints, low noise levels, and low maintenance requirements. The drive to develop lithium-ion batteries for electric vehicles and portable electronics has led to dramatic cost reductions in recent years [1], and it is widely expected that prices will continue to fall in future [2].

Co-location of energy storage with demand, for example by installing it in towns and cities (such as within houses [3] or at substations), can provide a number of key benefits over other locations. These benefits include peak shaving of both import and export (e.g. from embedded solar) and hence deferred infrastructure reinforcement, provision of backup power, power quality improvements, and increased self-consumption of embedded generation. Storage co-located with demand can also provide most of the benefits that can be provided by storage located elsewhere, such as reserve, footroom,[1] and frequency response.

In many cases, the benefits of operating storage are spread across a number of stakeholders. For example, self-consumption of rooftop solar photovoltaics (PV) using battery storage in a domestic property can lower the householder's electricity bills. It is possible, though not guaranteed, that this operation may consequently reduce peak flows on the local distribution network, thus benefitting the distribution network operator (DNO) and

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[1] *Footroom* is the ability of the system to absorb decreases in demand/increases in generation.

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Nomenclature

γ	Demand threshold
η_c	Charging efficiency of the storage, between 0 and 1
η_d	Discharging efficiency of the storage, between 0 and 1
d	Raw power demand (i.e. with no embedded generation or storage), ≥ 0
e	Energy contained in the storage, ≥ 0
$E_{\max}$	Maximum allowable energy level in the storage, >0
$E_{\min}$	Minimum allowable energy level in the storage, ≥ 0
N	Number of houses
p	Net power demand, after taking account of embedded generation and storage
$P_{c,\max}$	Maximum allowable charging power of the storage, >0
$P_{d,\max}$	Maximum allowable discharging power of the storage, >0
s	Output from the embedded generation (e.g. rooftop solar PV), ≥ 0
t	Time
u	Charging power of the storage, or discharging power if negative
ADMD	After diversity maximum demand
C-MADEnS	Consortium for Modelling and Analysis of Decentralised Energy Storage
CREST	Centre for Renewable Energy Systems Technology
DNO	Distribution network operator
HH	Household
HW	Hot water
PV	Photovoltaic
wd	Weekday
we	Weekend

subsequently other electricity consumers in the distribution area (by lowering future distribution charges). It may also reduce peak demands at a national level, thus reducing the country's generation capacity requirements and potentially displacing use of CO_2-emitting peaker plants, as well as providing footroom and lowering ramp rates in demand.

This paper describes an investigation into the potential of demand co-located electricity storage for peak shaving in low voltage distribution networks. Peak shaving could make it possible to defer reinforcement of distribution infrastructure as load growth occurs, e.g. from implementation of electric heating or electric vehicle charging. This paper is primarily concerned with the technical potential for peak shaving using storage, which is unaffected by price policy, therefore we do not consider price policy or economics here. The proportion of the technical potential that is achieved in reality depends upon the price policy that is implemented, but currently there are no real incentives for domestic peak shaving in the UK and many other parts of the world. This research is one element of the modelling work that forms part of a wider initiative looking at the role and value of energy storage within cities, within a research project titled 'Consortium for Modelling and Analysis of Decentralised Energy Storage' (C-MADEnS, www.c-madens.org).

1.2. Summary of previous work

Many recent studies have considered the use of energy storage for peak shaving. Luthander et al. [4] investigated the effects of storage and solar PV curtailment on peak shaving, showing that curtailment in particular can be used to halve peak PV export with less than a 7% annual loss in self-consumption. This study however has the limitation that the storage was operated simply to maximise self-consumption, rather than focusing on peak shaving explicitly.

A number of studies focus on control algorithms and pricing/incentive schemes for peak shaving, often in combination with some other goal (such as self-consumption of solar PV). Zheng et al. [5] developed a simple dispatch strategy for residential peak shaving from building-based energy storage, and investigated the economics of various storage technologies operating under a Con Edison demand tariff that charges consumers according to their maximum power demand during a one-month billing period. For the storage dispatch strategy, a "demand limit" was set, and the storage acted to try and maintain the household's power demand at the demand limit. By optimising the storage capacity and demand limit, it was found that annual profit from using storage can reach around 40% of the household's electricity bill, and that allowing occasional breaches of the intended demand limit increase profit.

Leadbetter and Swan [6] conducted investigations into the optimal sizing of battery storage systems for residential peak shaving, with results suggesting that typical system sizes should range from 5 kWh/2.6 kW for homes with low electricity usage, up to 22 kWh/5.2 kW for homes with high usage and electric space heating. Peak shaving of between 42% and 49% was reported in five regions of Canada. They also found that very little cycling is required for peak shaving, and that as such the system's life is limited by the calendar life of the batteries.

Hayes et al. [7] investigated individualised price policies to incentivise demand management, with the goal of reducing system demand peaks in such a way that the price tariffs seen by consumers are individualised and non-discriminatory. These exploit the demand awareness obtained from advanced metering infrastructure. Through a case study of residential users with energy storage in a typical European distribution network, the individualised price policy approach is shown to have advantages over a global price policy, where many users in the same network region are given the same price policy. These advantages included increased load factor, improved voltage and line loading conditions, and reduced network losses.

Others have focused on the effect of time-of-use tariffs on load shifting in residential areas with energy storage. Graditi et al. [8] considered the economics of electrochemical storage systems (including batteries and flow batteries) responding to time-of-use tariffs in Italy, focusing on their use within public institutions. Through case studies it is shown that at current costs, the use of battery storage systems is only economically feasible if there is a significant difference between the high and low prices in the tariff. Reductions in battery costs, and the introduction of support policies, will improve the economics of storage.

In the UK, much of the recent research into small-scale energy storage has been carried out within projects funded through Ofgem's Low Carbon Networks Fund. Yunusov et al. [9] used smart meter data to assess the impact of battery storage location (i.e. position on the feeder as well as whether on one or all three phases) on performance for peak shaving and phase balancing, focusing on two real low voltage networks. Some of the same authors have also considered real-time optimisation of DNO-owned storage being used for peak reduction, developing storage controllers that take into account demand forecasts and consumer