Journal of Energy Storage 18 (2018) 447–458

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Time-of-use and time-of-export tariffs for home batteries: Effects on low voltage distribution networks

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ARTICLE INFO

Keywords:
Electricity storage
Distributed energy storage
Smart meter
Peak shaving
Heat pump
Smart grid

ABSTRACT

Time-of-use electricity tariffs are gradually being introduced around the world to expose consumers to the time-dependency of demand, however their effects on peak flows in distribution networks, particularly in areas with domestic energy storage, are little understood. This paper presents investigations into the impact of time-of-use and time-of-export tariffs in residential areas with various penetrations of battery storage, rooftop solar PV, and heat pumps. By simulating battery operation in response to high resolution household-level electrical and thermal demand data, it is found that home batteries operating to maximise cost savings in houses signed up to time-dependent tariffs cause little reduction in import and export peaks at the low voltage level, largely because domestic import and export peaks are spread out over time. When operating to maximise savings from the first three-tier time-of-use tariff introduced in the UK, batteries could even cause increases in peak demand at low voltage substations, if many batteries in the area commence charging at the start of the overnight off-peak price band. Home batteries operating according to time-dependent electricity tariffs significantly miss out on the potential peak shaving that could otherwise be achieved through dedicated peak shaving incentives schemes and smarter storage control strategies.

1. Introduction

1.1. Background

With the rollout of smart meters in the UK, along with the regulator's desire to mandate half-hourly settlement of all electricity consumers based on their actual half-hourly consumption [1], there is considerable interest in the development of time-of-use (TOU) tariffs. These roughly align domestic electricity prices with demand, incentivising demand shifting [2,3] and use of energy storage systems (such as home batteries and hot water tanks) to reduce electricity demand at peak times. Similar developments are happening at varying rates around the world.

In the UK, TOU tariffs have historically existed as Economy 7 and Economy 10 tariffs, whereby consumers see lower off-peak electricity prices for seven or ten hours overnight. These were originally introduced in the late 1970 s to ensure consumption of overnight baseload power from coal and nuclear plants. With the decline in coal power, it is possible that fewer Economy 7 and Economy 10 tariffs will be available in the coming years. However, the growth of renewables, particularly variable renewables such as wind and solar, along with increasing penetration of embedded generation and active energy technologies such as electric vehicles (EVs) and heat pumps, exerts new stresses on the grid. The cost of network reinforcement in the UK is expected to reach up to £36bn by 2050 if we maintain passive approaches to network reinforcement and demand management [4], but these costs could be reduced significantly by taking advantage of smart demand technologies and appropriately incentivising their activity. These incentives could include new types of TOU tariffs.

Economy 7 and 10 tariffs have two price tiers, and are henceforth known as two-tier tariffs. Smart meters make it possible to add further tiers, allowing for tariffs that more closely reflect the full short-run social marginal cost of generating and distributing electricity, thus increasing economic efficiency [5]. Three-tier tariffs already exist in several countries (for example Canada [6]), and typically use a peak price tier to disincentivise use of electricity at peak times. A recent survey in the UK has shown that over a third of bill payers are in favour of switching to a three-tier TOU tariff, indicating a substantial potential market, with electric vehicle owners significantly more willing to switch [7]. Recently, the first three-tier TOU tariff was launched in the UK by Green Energy [8]. This tariff is known as 'TIDE', and at the time of writing (April 2018) its three tiers are an overnight off-peak rate of

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https://doi.org/10.1016/j.est.2018.06.008
Received 4 April 2018; Received in revised form 23 May 2018; Accepted 14 June 2018

Nomenclature

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 of the house (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
pNet	power demand of the house, 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 house's 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
ADME	After Diversity Maximum Export
CDM	CREST Demand Model
COP	Coefficient of performance of a heat pump
DNO	Distribution network operator
DUoS	Distribution use of system charge
EV	Electric vehicle
HH	Household
HW	Hot water
LV	Low voltage
RAG	Red-amber-green electricity tariff
SoC	State of charge of an energy storage device
TOU	Time-of-use tariff

6.41 p/kWh between 23:00 and 06:00, an evening peak rate on weekdays only of 29.99 p/kWh between 16:00 and 19:00, and a mid-peak rate of 14.02 p/kWh at all other times. Green Energy also offer a discount on the purchase cost of a home battery as an incentive to sign up to the tariff.

The price spread in Green Energy's TIDE tariff is particularly high; in Ontario, for example, there is a province-wide residential three-tier TOU tariff set by Ontario Energy Board, and prices range from 0.065 CAD/kWh off-peak to 0.132 CAD/kWh on-peak [6]. In Ontario, distinct summer and winter tariffs are used to account for the changing load profiles through the year, primarily because of significant variations in heating and cooling demands over the year. In Australia, typical off-peak prices in residential TOU tariffs are around 0.15 AUD/kWh, and typical on-peak prices are around 0.55 AUD/kWh [9,10]. This is a higher spread than in Ontario, but lower than that set by Green Energy in the UK.

In Great Britain, differential charging is also used by distribution network operators (DNOs) to cover the cost of operating the distribution networks. As a whole, these charges are known as Distribution Use of System (DUoS) charges, and three-tier tariffs known as red-amber-green (RAG) tariffs are used for non-domestic consumers with half-hourly settlement. A RAG tariff as used for DUoS charging typically has an off-peak *green price* time band overnight, a peak *red price* time band in the early evening, and *amber price* time bands in between [11]. DUoS charges for domestic consumers currently exist as a single rate (rather than being tiered), and are paid by suppliers acting as 'supercustomers', who pass the charges onto customers by factoring the costs in when developing tariffs.

Two-tier electricity tariffs have also been implemented in an effort to reduce reverse flow from solar PV in areas with high penetrations of solar power. In Cornwall, Regen SW, on behalf of the local DNO, Western Power Distribution, recently trialled a two-tier tariff known as the Sunshine Tariff [12]. This offered off-peak electricity from 10:00-16:00 for six months of the year (April to September). In that study, it was found that households with automation technology (such as a timed hot water immersion system) were able to shift 13% of their consumption into the 10:00–16:00 period, compared with 5% for those without automation [12]. Similarly low levels of engagement have been found in other TOU tariff trials, with field trials of TOU tariffs in 1500 German households resulting in average percentage reductions in peak demand of around 6% [13], and a pilot trial in 300 Cypriot households reducing total consumption in peak hours by no more than 3.5% [14]. In response to these low levels of engagement without automation, it has been recommended that automation and aggregators should be used for demand management [15].

Much research has looked at the possibilities for using energy storage for peak shaving on distribution networks. Recently, Pimm et al. investigated the potential of battery storage for peak shaving [16], assuming perfect foresight of net demand and perfect coordination of the storage. It was shown that in the UK, 3 kWh of battery storage per household could potentially allow a 100% switch to heat pumps without increasing peak demands at the secondary substation level. It was also shown that the export peak brought about by high levels of solar PV penetration (3 kW per household) could potentially be reduced to the level it would be if there were no PV by using 5 kW h of battery storage per household. These findings of large potentials for peak shaving using battery storage have been confirmed by Schram et al. [17], who also highlighted the importance of collaboration between households and other stakeholders, such as distribution system operators and retailers, to achieve the peak shaving potential at neighbourhood level.

Leadbetter and Swan [18] 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 kW h/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. It was 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.

Yunusov et al. [19] 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 (LV) networks. Some of the same authors have also considered real-time optimisation of DNO-owned storage being used for peak shaving, developing storage controllers that take into account demand forecasts and consumer clustering [20].

Zheng et al. [21] developed a control technique for peak shaving with battery energy storage systems using a demand limit. Whenever grid import is greater than the demand limit, the battery is discharged in an effort to bring import down to the demand limit, and whenever grid import is less than the demand limit, the battery is charged in an effort to bring import up to the demand limit. More recently, Babacan et al. [22] developed a convex optimisation approach to storage scheduling, and showed that residential electricity tariffs featuring demand charges and supply charges (proportional to monthly peak import and export) can reduce peak flows of electricity, reduce power fluctuations in net demand profiles, and increase self-consumption of solar PV.

1.2. Objectives

There exists a significant gap in the literature surrounding the effects on the distribution network of energy storage responding to time-of-use tariffs, even though it is likely that distribution networks will