# Flexible Operation of Shared Energy Storage at Households to Facilitate PV Penetration

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***Abstract***—This paper proposes a new methodology to enable high penetration of photovoltaic (PV) generation in low voltage (LV) distribution networks by using shared battery storage and variable tariffs. The battery installed at customer premises is shared between customers and local distribution network operators (DNOs) to achieve two goals- minimizing energy costs for customers and releasing distribution network constraints for DNOs. The two objectives are realised through a new concept - "charging envelope", which dynamically allocates storage capacity between customers and the DNO. Charging envelope first reserves a portion of storage capacity for network operator's priority to mitigate network problems caused by either thermal or voltage limit violation in order to defer or even reduce network investment. Then, the remaining capacity is used by customers to respond to energy price variations to facilitate in-home PV penetration. Case study results show that the concept can provide an attractive solution to realise the dual conflicting objectives for network operators and customers. The proposed concept has been adopted by the Western Power Distribution (UK) in a smart grid demonstration project SoLa Bristol.

***Keywords*** **—**Energy management, energy storage, charging envelope, PV, demand response, tariff.

## 1. Introduction

The penetration of photovoltaic (PV) generation in low voltage (LV) networks is increasing across the UK, projected to be 22GW by 2030. Along with benefits, the increasing PV also causes significant thermal and voltage violations for LV networks. Traditional approaches address these problems through network reinforcement, which is both expensive and time-consuming. Alternatively, demand side response (DSR), through sending economic signals, is an economic way to alter customer's energy use to ideally follow PV output [1-4]. From this aspect, energy storage empowers customers more flexibility in conducting DSR to maximise the benefits and help mitigate network issues caused by the increasing renewables [5].

Previous research [6-10] has been dedicated to using DSR and energy storage to tackle network issues with fluctuating renewable generation. Paper [11] proposes a novel active robust optimization dispatch by using robust optimization (RO) to study the impact of price responsive DSR, considering all possible wind power scenarios in a system. Papers [12, 13] present an overview of challenges in integrating PV power into distribution networks and illustrates a variety of operational modes for battery storage systems to enable PV integration. In paper [14], a thermal unit commitment program is proposed which considers DSR for meeting system constraints, where electric vehicles (EVs) and heat pumps (HPs) are considered as controllable loads for enabling DSR. Paper [15] presents a multi-objective optimization method for

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evaluating the impact of energy storage costs on the net present value of installations in distribution substations. It uses a non-dominated sorting genetic algorithm (NSGA) optimization for load management to reduce costs. Paper [7] formulates a non-cooperative game model to analyse the existence of optimal strategies for customers with energy storage to reduce energy costs, where smart metering is considered. In paper [16], authors propose a method for coordinating multiple battery energy storage systems for voltage control in LV distribution networks. Generally, the existing work normally targets at either reducing energy costs for customers or releasing network pressures for Distribution Network Operators (DNOs), but the two problems are not resolved simultaneously.

In a low carbon energy system with substantial intermittent generation penetration, energy cost pressures may conform to network pressures (voltage or thermal problems), i.e. when demand is at peak (normally energy cost is high), renewable generation could also be at peak. Thus, energy storage is better not only used for reducing customers' energy costs but also for shaving system peak demand. The joint operation of DSR and energy storage can efficiently reduce energy cost and release network congestions. This is a dual-objective problem and papers [8, 17] are the first effort to address it. They introduce a joint ownership of battery storage between customers and local DNOs to mitigate high energy costs and reduce network congestions. However, they assume a 'static' ownership sharing scheme, i.e. the share between customers and DNOs does not change with the variations of energy prices and network conditions.

In reality, PV output, customer energy consumption, and network conditions vary dramatically with time, and thus a flexible share of energy storage can maximise the potential benefits for both parties. The shared energy storage is invested by the DNO but can be operated by both the DNO and the customer at whose premise the storage installed. The primary target of DNO to operate it is to help manage the networks, i.e. resolving voltage and thermal limit violations. Then, the remaining capacity is utilised by the customers to manage their PV output and energy use in response to variable electricity tariffs. This problem could be modelled as a dual or multi-objective problem, but the simultaneous optimisation could not reflect the management sequence.

This paper introduces a new solution to tackle the conflicts between the aims to address network pressures and energy costs simultaneously by utilising a shared energy storage. It proposes a novel concept of "charging envelope" to realise a joint storage ownership between DNOs and customers to achieve a dynamic share of the storage capacity in response to network conditions and energy prices. DNOs reserve a proportion of the capacity during projected network congestion periods to discharge energy for resolving voltage or thermal issues. Within the constraints of charging envelope, the remaining storage capacity is for customers to minimise energy costs via responding to energy tariffs and maximising PV penetration. The key advantages of the solutions are that they provide DNOs with greater certainty in mitigating network thermal or voltage violation problems. The concept has been utilised in a smart grid demonstration project in the UK. The major contributions are: i) a new approach to enable joint flexible battery share between DNOs and customers; ii) a new battery operation strategy based on time-of-use tariffs for customers to optimise energy costs.

## 2. Rationale of Designing Charging Envelopes

This section briefly introduces the SoLa Bristol project which adopts the proposed approach, the

concept of shared energy storage, and finally, charging envelops.

### 2.1 SoLa Bristol Project

The SoLa Bristol project is an innovative combination of energy storage in customer premises, variable tariffs, and integrated LV network control techniques to overcome network constraints at key times of a day [18]. It is jointly sponsored by Western Power Distribution and UK market watchdog- the Office of Gas and Electricity Markets (Ofgem). This project supported 26 homes, 5 schools and an office block in Bristol to benefit from the new energy management concept [19]. It aims to address the technical constraints expected to arise on LV networks caused by increasing PV penetration with the assistance of energy storage. Through reducing network constraints and needed reinforcement, the trial techniques will facilitate PV penetration at a reduced cost. The sizes of PV and battery storaged installed are 3.5kWp and 4.8kWh respectively.

### 2.2 Shared Energy Storage

The trial project uses battery storage installed at customer households, invested by the DNO in this project, to provide benefits to customers and assist the DNO in network management. The battery is "virtually shared" between the customer and DNO. The DNO is able to communicate with the battery to operate it for network management. The DNO who invests the storage has the priority to use the battery storage. The main purposes are to resolve the thermal limit violation and voltage limit violation in the networks to reduce network investment. Then, the remained capacity of the storage not used by the DNO can be operated by the customer where the storage is installed. The customer is provided with variable tariffs to be encouraged to use electricity at the time of high PV generation and electricity from the storage when the network is heavily loaded. The customer who operates the remaining capacity mainly targets at maximising its PV output in order to reduce energy costs.

Through the storage, LV networks can be operated more actively with additional capacity to manage peak load and voltage rise [19]. For customers, the storage can enable high-density PV generation to be connected to the LV network more efficiently.

### 2.3 Charging Envelope Design

A charging envelope is to flexibly determine the capacity of battery storage operated by DNOs for addressing electricity network voltage and thermal issue. As given in Fig.1, charging envelopes are the boundaries that define and constrain storage state of charge (SoC), including start time, duration and slope of charging/discharging. The upper and lower boundaries constrain the maximum and minimum SoC respectively for two purposes: i) resolving network pressures; ii) supplying DC load during discharging periods and accommodating PV penetration.

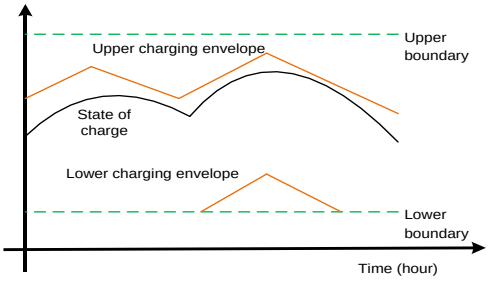

Fig. 1. The relation between charging envelope and real-time SOC.

As seen in Fig.1, the increasing slope of the upper boundary of the charging envelope limits the change of storage SoC, decided by the energy from PV and the grid. The decreasing, i.e. discharging, slope of the upper boundary represents the minimum drop of SoC. The decrement is discharged energy for mitigating network voltage or thermal problems. Similarly, the lower boundary of the charging envelope is the minimum energy required to charge for mitigating network congestions and avoiding energy released from the battery. Ultimately, the SoC should be within the upper and lower boundaries in order to flexibly respond to the variations of network conditions and energy prices.

Charging envelope design involves the following steps:

a) to define charging envelopes that are only for maximizing PV by assuming no congestions in the LV network output into the system (Base case). This is related to Section 4;
b) to determine the levels and durations of network issues of thermal or voltage limit violations. This is related to Section 5;
c) to determine required charging and discharging energy during the periods that the network has thermal or voltage issues in step b). This is related to Section 5;
d) to determine the increasing and decreasing slopes of the upper and lower boundaries of charging envelops. This is related to Section 5;
e) to extend the designed charging envelopes to accommodate varying network constraints. This is related to Section 5;
f) to conduct battery charging and discharging within charging envelopes in response to variable energy tariffs for end customers. This is realised in Section 6.

### 2.4 Discussion on Charging Envelope

The designed charging envelopes are employed to manage the SoC of the battery storage shared between network operators and customers, which includes the charge/discharge start time, duration and charging/discharging slope of energy storage. The storage is jointly operated by network operators and customers for different purposes: resolving network issues, such as overloading and voltage violation, and reducing energy bills and maximise PV penetration, respectively. The envelops aim to maximise the use of battery storage for the two parties.

Charging envelopes have an upper and lower charge window, and the storage's SoC is constrained within the range. From the perspective of the physical features, the maximum and minimum SoCs are decided by the basic attributes of the storage. Practically, the SoC of the storage is constrained within 20%~90% of its rating for security reasons as deep charging and discharging adversely impact its lifespan. Both charging and discharging slopes in charging envelopes are linked to the degrees of network stresses, such as overloading, voltage violation, and solar generation output. In general, the discharging envelops are mainly designed for peak demand reduction during winter periods, and the charging envelops are designed to absorb high PV generation during high summer.

In practice, network operators have the priority to operate the storage, i.e. they use part of the storage capacity first and the remaining capacity is used by customers. Network operators can communicate with the storage via intelligent control to modify the charging envelopes to aid network management.

Therefore, both physical constraints of the battery and network constraints are taken into consideration when determining the charging envelope. For end customers, the storage optimisation for minimising energy bills is operated within the upper and lower constraints dictated by the charging envelope. For different types of network constrains and customer constraints with varying strengths and durations, the key parameters of the charging envelopes will be modified to reflect these factors in operation [20].

## 3. System Configuration

This section introduces the configuration of the charging path of energy storage, customer load files, and PV output.

### 3.1 Configuration of Charging and Discharging Paths

Charging envelopes are designed to manage battery SoC, where all possible scenarios that could lead to SoC variations need to be considered. It is thus necessary to find storage charging and discharging paths and the corresponding directions of energy flows. It is assumed that the energy system has four parts: grid, PV, battery storage, and DC load. A DC network is installed besides the existing AC network at the costumer site and major DC load is lighting and computing equipment. It is assumed that the AC load is met by grid supply and thus not modelled here. The system layout is given in Fig. 2.

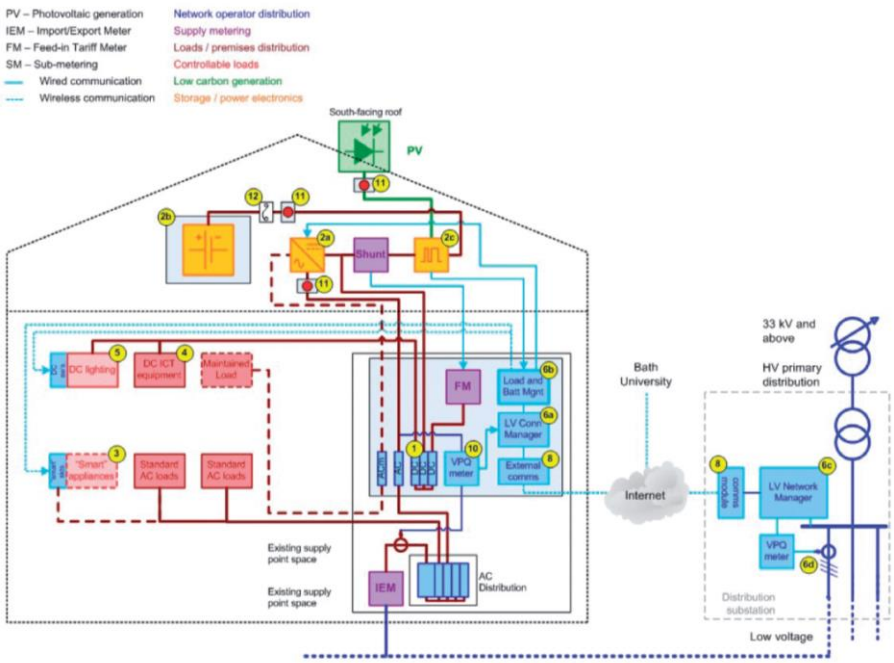


Fig 2. The system overall layout [21]

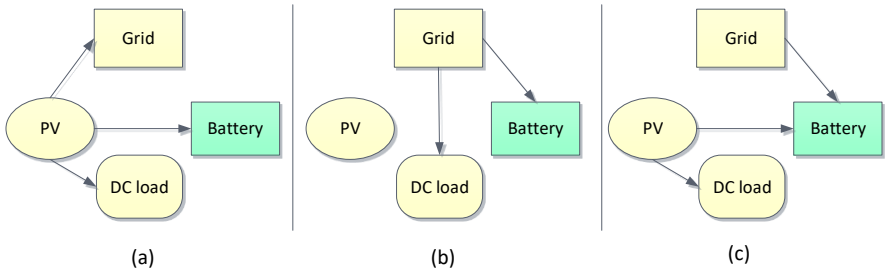

Fig. 3. (a) PV charging - charging path 1; (b) Grid charging -charging path 2; (c) Hybrid charging path - charging path 3.

a) Depending on PV output, battery charging paths can be classified into three types, illustrated in Fig.3. The solid arrows represent actual power flow directions.
b) In charging path 1 (PV charging path), the power to charge battery storage and support local DC is from PV, where the extra energy is exported to the main grid.
c) In charging path 2 (grid charging path), the battery withdraws energy totally from the main grid and the energy for supporting the DC load is also from the grid.
d) In charging path 3 (hybrid charging path), PV output is to charge the battery and support DC load. Any energy shortfall is imported from the main grid.
e) Two battery discharging paths are defined, shown in Fig.4:
f) In discharging path 1 (unidirectional discharging path), the battery is discharged to supply the DC load.

In discharging path 2 (bidirectional discharging path), the battery storage supports the DC load and also exports energy to the main grid.

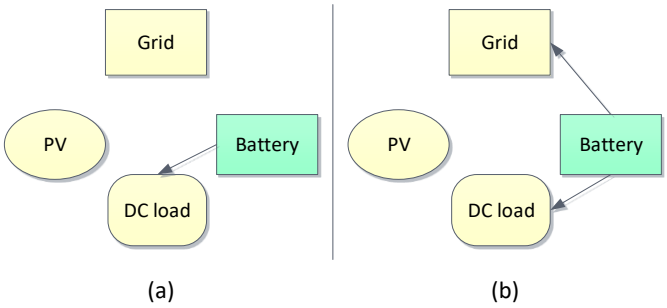


Fig. 4. (a) Unidirectional discharging path- discharging path 1; (b) Bidirectional discharging path - discharging path 2.

### 3.2 Customer Load Profiles and PV Output

Normally load demand and PV output vary dramatically over time, leading to different shapes of charging envelopes. The typical load profiles [22] and PV output [21] of a typical UK domestic household in each season are used. For simplicity, Fig.5 only provides the profiles on a typical winter day across 48 settlement periods. Generally, AC load demand in winter is higher than that in other seasons, which peaks in the early evening close to 2kW. The charging envelopes for battery storage in different seasons are designed based on the typical profiles load and PV output.

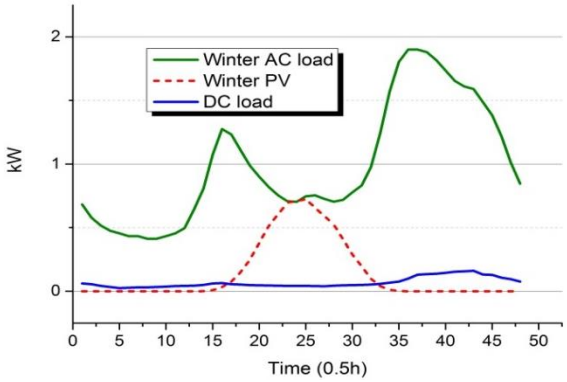


Fig. 5. Load and PV generation profiles in winter.

### 3.3 Flowchart of the Proposed Method

The flowchart of the proposed method is given in Fig. 6. It includes all inputs: load profiles, PV output, Electricity tariffs, and storage specifications. These inputs are then used for charging envelop design in two cases. Finally, the method will produce the outputs of shifted load profiles, energy storage operation strategies, and benefits for end customers and DNOs.

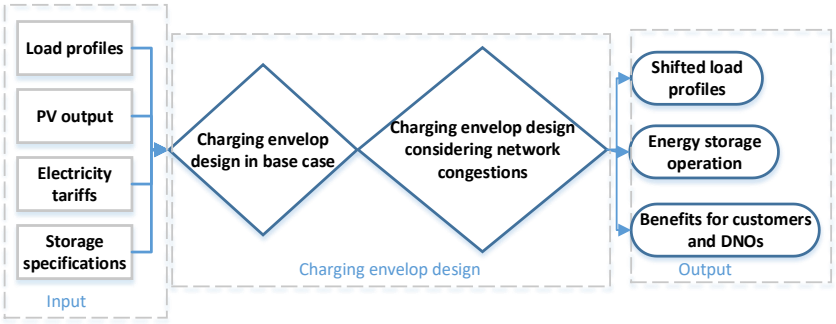


Fig 6. Flowchart of the proposed method

## 4. Charging Envelope Design in Base Case

This section designs charging envelopes based on the assumption that there are no LV network congestions. Thus, the storage is purely used to store the excess energy from PV and enable the shifting of energy consumption for reducing costs.

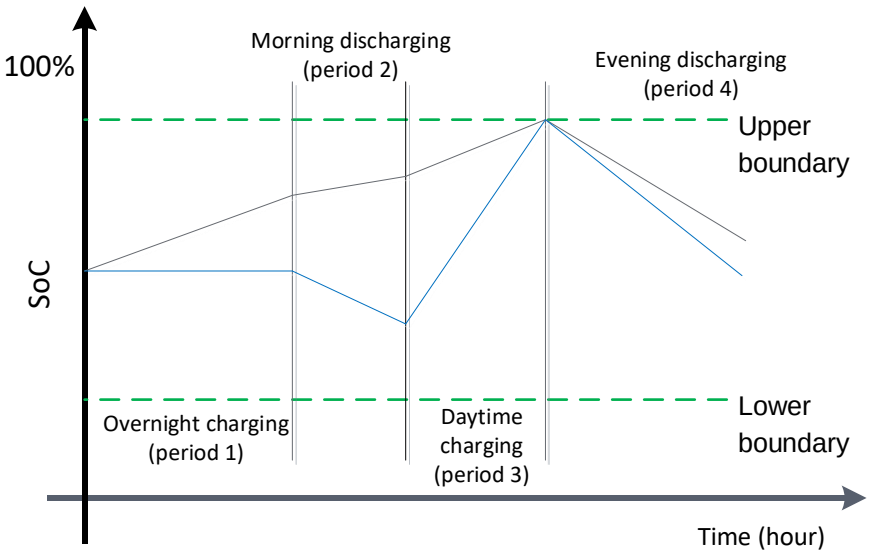


Fig. 7. Differentiation of charging and discharging periods.

Beforehand, it is essential to determine the periods of charging and discharging in a settlement day. According to PV output and load profiles in Fig.7, there are roughly four periods [23]: overnight charging (Period 1), morning discharging (Period 2), day-time charging (Period 3), and evening discharging (Period 4). Period 1 is to charge the battery storage in response to off-peak energy prices and Period 2 is to discharge the stored energy and prepares for charging in Period 3. In Period 3, because the PV output is mainly in daytime, therefore storage charging is encouraged. In Period 4 because there is few PV output and peak demand occurs in this time period, thus the storage is discharged in this period. Charging envelopes are developed for each season respectively in order to reflect that load and PV output varies throughout a year.

### 4.1 Daytime Charging Slope and Duration (Period 3)

The charging envelope design in Period 3 is primarily for promoting PV generation. It can be arbitrarily set as the shortest period with no less than a certain percentage of daily PV output, for example, 90%. In this charging period, daily PV output in a household is assumed to follow normal distribution considering its uncertainty [23]

$$G \sim N(\mu, \delta^2) \tag{1}$$

where, $\mu$ is the average PV output and $\delta$ is the standard deviation.

If the confidence interval is selected as 1-$\alpha$, the confidence interval for $\mu$ is [24]

$$(\overline{X} \pm \frac{S}{\sqrt{n}} t_{\alpha/2}(n-1)) \tag{2}$$

where, $n$ is the number of generation samples, and $X$ , $S$ are average PV output and standard deviation.

The daily minimum PV output is

$$G_{\min} = \overline{X} - \frac{S}{\sqrt{n}} t_{\alpha/2}(n-1) \quad (3)$$

The SoC has an increment of $G_{min}$ during charging, equal to the reserved capacity $C_{da\_ch}$. It is reflected as the increasing level of SoC in the upper boundary of the charging envelopes.

### 4.2 Evening Discharging Slope and Duration (Period 4)

During this period, because the load is generally high and thus the storage discharging is to provide energy for the DC load. The discharging period starts after charging the battery storage in Period 3 and the storage will support the DC load until the end of evening peak period. The time duration is $T_{ev}$ and the discharging slope is determined by DC load level. The reserved capacity is

$$C_{ev\_dis} = L_{DC,ev} \cdot T_{ev} \quad (4)$$

where, $C_{ev\_dis}$ is the reserved battery capacity and $L_{DC,ev}$ is the maximum DC load in the period.

The reserved capacity for discharging to support the DC load is the SoC decrement in the upper boundary in Period 4.

### 4.3 Overnight Charging Slope and Duration (Period 1)

The needed charging energy in Period 1 is the difference between the upper SoC boundaries at the beginning of Period 3 and at the end of Period 4.

- If SoC at the end of Period 4 is lower than that at the beginning of Period 3, it means the battery storage has lower energy and thus it can charge by withdrawing energy from the grid in Period 1 of the following day, where energy price is low.
- Otherwise, storage charging is not desirable in Period 1 and the upper boundary is flat.

The charging starts from the end of Period 4 until morning peak time, where the reserved capacity is

$$C_{ov\_ch} = \begin{cases} S_{da,be} - S_{ev,en} & if\ S_{da,be} > S_{ev,en} \\ 0 & Otherwise \end{cases} \quad (5)$$

where, $C_{ov\_ch}$, $S_{da,be}$ and $S_{ev,en}$ are reserved storage capacity for charging, SoC in the upper boundaries at the beginning of Period 3 and at end of Period 4.

### 4.4 Morning Discharging Slope and Duration (Period 2)

In Period 2, the storage can release energy to support the DC load. The discharged energy is

$$C_{mo\_dis} = \begin{cases} L_{DC,mor} \cdot T_{mor}, & if\ S_{da,be} < S_{ev,en} \\ 0 & Otherwise \end{cases} \quad (6)$$

where, $C_{mor\_dis}$ is the reserved capacity for storage discharging in the morning. $L_{DC,mor}$ is the maximum DC load level in the time interval and $T_{mor}$ is the length of Period 2 [23].

## 5. Charging Envelope for Mitigating Network Issues

This section extends the designed charging envelopes in Section 4 to mitigate network overloading and overvoltage issues. In networks with thermal limit or voltage limit violations, more energy is needed to meet local load. Then, steeper discharging slopes are essential to enable fast battery response.

### 5.1Thermal Limit Violation Case

If the power flow along a branch or through substation is higher than the power rating, the thermal limit is violated. The charging envelope aims to release more energy for mitigating the overloading. System demand contribution from each feeder to the substation level at each time point is estimated by

$$d_{sy,i} = d_{h,i} \cdot N \cdot cf \tag{7}$$

where, $d_{sy,i}$ and $d_{h,i}$ are system and household demand in the $i^{th}$ settlement period respectively. $N$ is customer number served by the substation, and $cf$ is coincidence factor.

In a discharging period, the overloading degree of each branch/substation is estimated by (8)

$$L_{ol\_ther} = d_{b\_ther} - d_{ther} \tag{8}$$

where, $L_{ol\_ther}$ is overloading level, $d_{b\_ther}$ is the peak demand along an asset, and $d_{ther}$ is the maximum load that the asset can support.

The power discharged by the storage for resolving network overloading is designed by allocating the overloading to all households with demand diversification considered

$$R_d = \frac{L_{ol,i}}{N_p \cdot cf_{dis}} \tag{9}$$

where, $N_p$ is the customer number having a battery storage to relieve network congestion, $R_d$ is discharged power, and $cf_{dis}$ is the coincidence factor for discharging the battery.

Thus, in overloading periods, the additional storage capacity reserved for mitigating the overloading is

$$C_{ol\_ther} = R_d \cdot T_{ol\_ther} \tag{10}$$

where, $T_{ol\_ther}$ represents overloading duration.

### 5.2 Voltage Limit Violation Case

When LV network voltage is out of statutory range, currently [-6%, +10%] in the UK, it is defined as voltage limit violation. The per unit voltage drop along a feeder is [25]

$$\Delta V \approx \frac{P \cdot R + Q \cdot X}{V} = \frac{S \cdot \cos\theta \cdot R + S \cdot \sin\theta \cdot X}{V} \tag{11}$$

where, $P$ and $Q$ are unit active and reactive power along a feeder, $V$ is voltage at feeder beginning, $R$ and $X$ are unit values of resistance and reactance, and $cos\theta$ is power factor.

The overvoltage level is defined as

$$\Delta V_{ol} = \left|\Delta V\right| - \left|\Delta V_{B,\min}\right| \tag{12}$$

where, $\Delta V_{B,min}$ is the maximum allowed voltage drop.

Voltage violation can be converted into overloading level

$$L_{ol\_vol} \approx \frac{\Delta V_{ol} \cdot V \cdot S_{Base}}{R \cdot \cos\theta + X \cdot \sin\theta} \tag{13}$$

where, $S_{base}$ is the base power.

The storage capacity for resolving this problem is

$$C_{ol\_vol} = \frac{L_{ol\_vol}}{N_{p,ol} \cdot cf_{dis}} \cdot T_{ol\_vol} \tag{14}$$

where, $T_{ol\_vol}$ is the duration of the thermal limit violation.

Once the additional capacity of storage reserved for resolving network constraint is quantified, a decrement of $C_{ol\_ther}$ or $C_{ol\_vol}$ in SoC can be reflected in the upper boundaries of the charging envelopes. It should be noted that when PV output is high, reverse power flow might appear and it could cause voltages at feeder ends to violate upper statutory limits. Thus, more charging capacity is reserved to reduce reverse power flows. The additional storage capacity reflected in the boundaries of charging envelope can be designed by using the same method used for releasing thermal limit violations.

## 6. Storage Operation Algorithm

The main operation objective of the remaining storage capacity by customers within a settlement day is to respond to energy prices in order to minimise the cost of purchasing electricity from the main grid. With predictions of day-ahead load profiles and PV output, the problem is formulated as an optimisation

$$min \quad C_{gr} = \sum_{i=1}^{48} e_i \cdot d_{new,i} \cdot t \cdot \alpha \tag{15}$$

where, $C_{gr}$ is the total cost of purchasing energy from the main grid. $e_i$ and $d_{new,i}$ are tariff rate and power imported from the grid in the $i^{th}$ settlement period. $t$ is the length of each settlement period, assumed to be 0.5 hour. $\alpha$ is the percent of energy cost in customer final electricity bills.

The imported power from the main grid in the $i^{th}$ settlement period is determined by the amount of local AC and DC demand, battery charging power, and PV generation

$$d_{new,i} = \max(d_{h,i} + d_{DC,i} - g_{PV,i} + \frac{(S_{i+1} - S_i)}{t}, 0) \tag{16}$$

where, $i$ is settlement index, $d_{DC,i}$ and $g_{PV,i}$ are household DC demand and PV output, and $S_i$ is SoC level. The difference between $S_{i+1}$ and $S_i$ is the battery charging/discharging amount.

In addition, the optimization model should meet the following constraints:

a) For simplicity, it is assumed that the net battery charging/discharging energy is zero in a settlement day. Thus, the SoC at the end of a settlement day is equal to that at the beginning of the day. If 48 settlement periods are considered, the constraint is

$$S_{49} = S_1 \tag{17}$$

b) The battery SoC should be within the upper and lower boundaries of charging envelopes

$$S_{lo,i} < S_i < S_{up,i} \tag{18}$$

where $S_{up,i}$ and $S_{lo,i}$ are the maximum and minimum allowed SoC in the upper and lower boundaries of the charging envelopes in the $i^{th}$ settlement period.

c) The charging and discharging rates are within a certain range

$$0 < S_{i+1} - S_i < p_{ch} \quad (19.\text{a})$$

$$0 < S_i - S_{i+1} < p_{dis} \quad (19.\text{b})$$

where, $p_{ch}$ and $p_{dis}$ are battery charging and discharging power rate limits.

d) In charging, the actually charged power should be higher than SoC increasing rate constrained by the upper and lower boundaries of charging envelopes in (20.a). In discharging, the actually discharged power should be higher than the SoC decreasing rate confined by upper and lower boundaries of charging envelopes in (20.b) [23].

$$S_{i+1} - S_i \geq \max(S_{up,i+1} - S_{up,i}, S_{lo,i+1} - S_{lo,i}) \quad (20.\text{a})$$

$$S_i - S_{i+1} \leq \max(S_{up,i} - S_{up,i+1}, S_i - S_{lo,i+1}) \quad (20.\text{b})$$

This problem is a discrete optimisation with linear objective and constraints. It is resolved by CPLEX in Matlab [26].

## 7. Results of Charging Envelops

The proposed approach is implemented in a UK Low Carbon Fund smart grid demonstration project-SoLa Bristol. A typical LV network from the demonstration area is selected for illustration on four typical settlement days of four seasons.

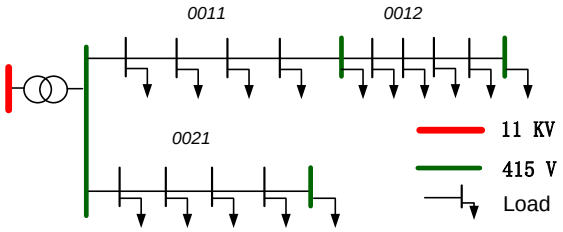


Fig.8. The layout of a typical radial LV network.

The LV network in Fig. 8 has three main feeders, numbered as 0011, 0012 and 0021 [21]. The parameters of all feeders and the 11/0.415kV transformer are given in [17]. Power factor and coincidence factors are assumed to be 0.95 and 0.8 respectively [27]. It is supposed that all households connected to the feeders are equipped with PV panel of capacity 3.5kWp and battery storage of 4.8kWh. The SoC of the storage is constrained within 20%~90% of its rating for security reasons as deep charging and discharging adversely impact battery storage lifespan.

### 7.1 Base Case Study of Charging Envelopes

By using time-series analysis, the maximum utilization of the transformer is found to be 48.4%. According to PV output samples from [21], the standard deviation is 1.03 and the confidence is 0.95. In this case, because there is no network congestion, charging envelopes are assumed to be identical for all households with similar load profiles and battery size.

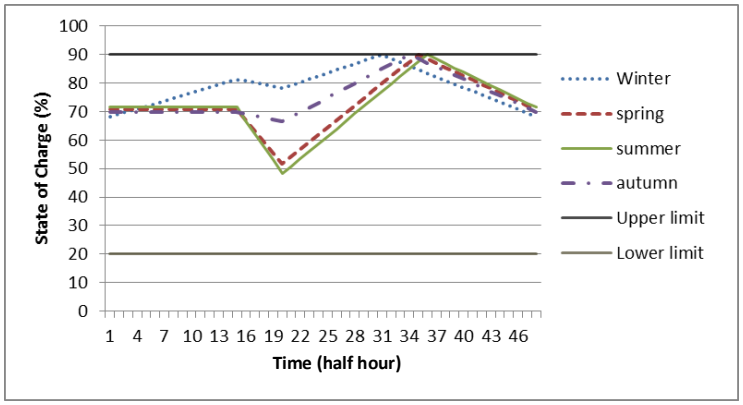


Fig.9. Charging envelopes for the base case.

By using these inputs, the charging envelopes in different seasons are shown in Fig.9. It is observed that the upper boundaries in daytime charging periods vary significantly across seasons. In evenings, the decrease of upper boundaries indicates that the reserved storage capacity for discharging from 16:00 onwards is similar for all four seasons. This is mainly because that the total discharged energy is primarily for supporting the local DC demand rather than mitigating network congestions. During low PV output seasons, the maximum allowed SoC increases by 8% before 6:00. It means that 8% storage capacity is reserved for charging from the grid during overnight off-peak periods in addition to daytime PV charging.

### 7.2 Charging Envelopes for Mitigating Network Congestion

This section shows the design of charging envelopes with network congestions by scaling up demand level in the previous case. Time-series analysis illustrates that feeders 0011 and 0021 undergo thermal limit violations in the early evening on the selected winter day. Due to different degrees, types and durations of network overloadings, one uniform type of charging envelopes are inappropriate for all storage to resolve the network congestions. Thus, they should be designed separately, and according to network conditions, two types of charging envelopes are designed in Fig.10.

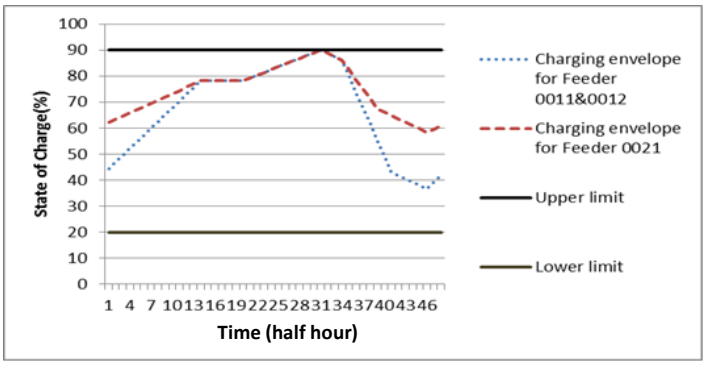


Fig.10. Charging envelopes for the overloading case in winter.

Compared to Fig.9, there are dramatic decreases of the upper boundaries for both charging envelopes from 17:00 onwards, illustrating by the dotted and dash lines in Fig.10. The decrements indicate that increasing storage capacity is reserved for mitigating network overloading for DNOs. The reserved storage capacity along feeders 0011 and 0012 is around 43%, nearly two times of that for feeder 0021,

which is 19%. It is mainly caused by the higher degree and longer durations of the overloading along feeders 0011 and 0012.

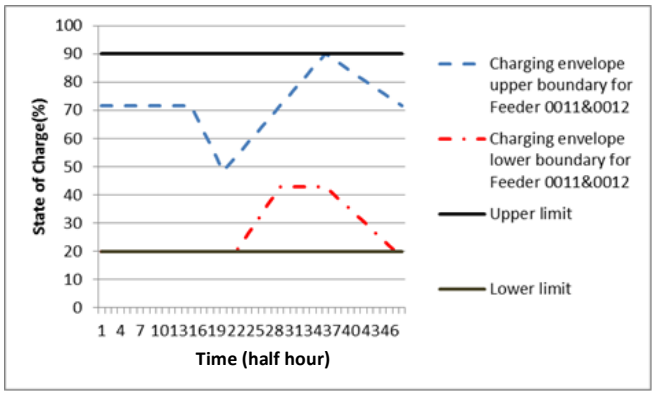


Fig.11. Charging envelopes for over voltage case in summer.

The charging envelopes in summer for mitigating overvoltage due to PV output are plotted in Fig 11, which are derived by assuming that the voltage at the substation is 1.075p.u and the daily PV out is 25.37 kWh at the maximum confidence. The charging envelopes are only for the storage along feeders 0011 and 0012, whose voltages are out of statutory range. The red dash line shows that from 10:30 to 14:00, the lower boundary increases from 20% to 43% and the reserved capacity is for reducing voltage rise caused by PV output.

## 8. Benefits Quantification

Once charging envelopes are defined, they are then used to investigate how customer load profiles are affected when the remaining energy storage capacity is operated in response to energy tariffs. The tariffs employed in this study are time-of-use (TOU) designed based on the energy price variations in [28] [29], which can capture the price variations without comprising the accuracy. In this case study, the CAPEX and OPEX of the battery storages are not considered.

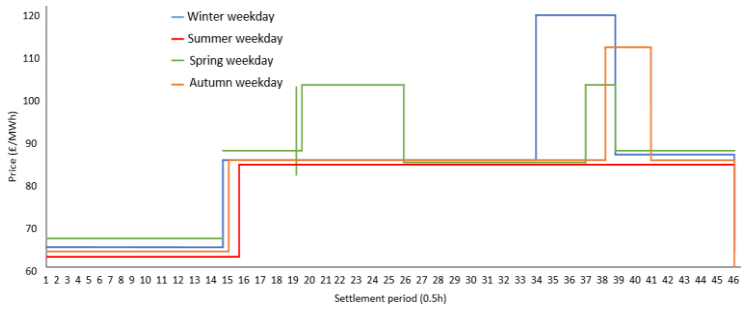


Fig.12. Variable tariffs in different seasons.

The tariffs shown in Fig.12 are used for the energy storage operation controlled by customers within the charging envelopes. In each season, there is a typical tariff profile for each day, which varies dramatically. In the typical spring day, the profile has two peak periods, but the summer day does not

have an apparent tariff peak. Both typical winter and autumn days have one peak-price time interval, but the degree and duration in the winter day are much higher/longer than those in the autumn day. The highest tariff is around 120£/MWh in winter, and the lowest is 63£/MWh in summer. In addition, the summer day has the lowest peak price around 88£/MWh.

TABLE I

AGGREGATED BENEFITS IN BASE CASE FOR CUSTOMERS

| | With envelope | | Without envelope | |
|---|---|---|---|---|
| | Peak reduction (MW) | Energy cost saving(£) | Peak reduction (MW) | Energy cost saving(£) |
| Winter day | 0.052 | 48.4 | 0.044 | 46.6 |
| Spring day | 0.062 | 126.7 | 0.058 | 120.8 |
| Summer day | 0.033 | 114.9 | 0.030 | 109.4 |
| Autumn day | 0.051 | 98.5 | 0.045 | 94.5 |

When the remaining storage capacity confined by charging envelopes is used to minimise energy costs for customers, the aggraded benefits in terms of energy cost savings for all customers and peak demand reduction for DNOs are provided in Table I. By comparing the case without charging envelope, it is found that the case with charging envelopes can further reduce system peak demand and increase customer savings. As seen, the biggest peak demand reduction difference is on the Winter Day, which is 0.008MW. On the other hand, the highest energy cost saving difference is on the Spring day, which is calculated as £5.9. The peak demand reductions on the four days fluctuate between 0.033 MW and 0.062 MW, where the most effective shaving is in spring. The two main factors for the largest benefits in spring are sufficient PV generation and relatively cheap energy prices. Compared with the scenario where energy storage purely responds to variable tariffs without charging envelopes, the new approach with charging envelopes produces increments in both energy cost saving and peak reduction in all four seasons. The maximum difference in peak demand reduction is 0.008MW in the winter day and maximum cost saving is £5.9 in the spring day.

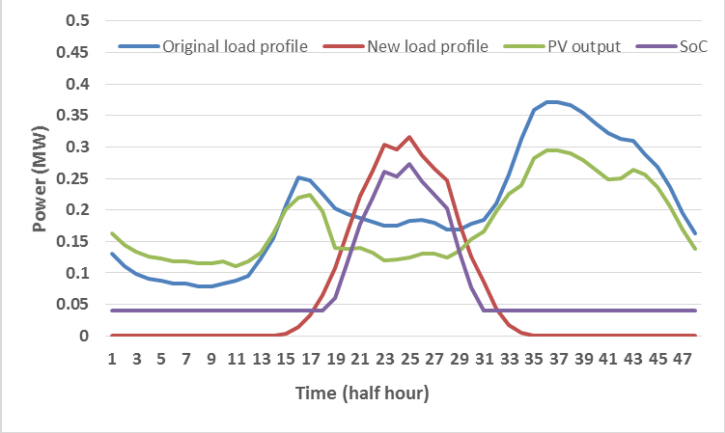


Fig.13. Aggregated load at the substation with overloading in winter.

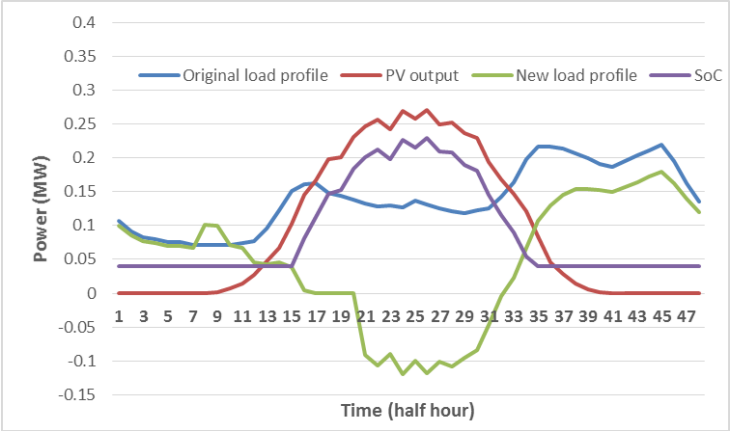


Fig.14. Aggregated load at the substation with over generation in summer.

Figs.13 and 14 demonstrate load profile changes at the substation by adopting charging envelopes on the typical winter day with network overloading and on the summer day with voltage violation. The original load profiles are the measured data in the demonstration substation. The charging envelopes are not used on the spring and autumn days as no network constraints appear. The load profiles in Fig.13 shows a reduction of 0.082MW in peak demand because of energy storage. The demand during daytime is significantly reduced because of PV output. Meanwhile, as illustrated in Fig.14, the maximum reverse power flow in summer is 0.122MW, also caused by abundant PV generation. Therefore, the reservation of energy storage capacity in charging envelopes is effective for resolving network thermal constraints. Here, the negative demand profile means that customers sell electricity back to the grid, where the unit price is 3p/kWh based on UK feed-in-tariff.

TABLE II

AGGREGATED BENEFITS IN THE CASE WITH NETWORK CONGESTIONS

| | With envelope | | Without envelope | |
|---|---|---|---|---|
| | Peak reduction (MW) | Cost saving(£) | Peak reduction (MW) | Cost saving(£) |
| Winter day | 0.082 | 62.7 | 0.044 | 46.6 |
| Summer day | 0.041 | 117.3 | 0.030 | 109.4 |

Aggraded energy cost savings for all end customers and network peak reductions in the two scenarios are given in Table II. On the winter day, the peak demand reduction is almost twice high in the case with charging envelops, 0.082MW compared to 0.044MW. The daily energy cost savings on the winter and summer days are £62.69 and £117.30. It is also observed that the implementation of charging envelopes can produce additional energy cost saving of £16.11 on the winter day.

## 9. Conclusions

This paper proposes an innovative concept of charging envelope for energy storage management by

sharing the storage between network operators and customers. This new concept can realise energy cost minimization for end customers and network constraint mitigation for network operators, as demonstrated in the case study. In networks with congestions, steeper discharging slopes in upper envelope boundaries are required to release severe network stresses. By contrast, steeper charging slopes are needed in low boundaries to relieve network pressures caused by over PV generation. In the test system with network congestions, additional daily energy cost savings up to 34% could be realised with the proposed charging envelopes. System peak demand reduction increases from 12% to 22%. The application of charging envelopes is very effective in realising dual objectives of realising network pressures and reducing customer energy costs. Future work will be extended to year-round analysis without assuming that the daily net storage energy to be zero.


[1] C. Gu, F. Li, and Y. Song, "Long-Run Network Pricing to Facilitate Users' Different Security Preference," *Power Systems, IEEE Transactions on,* vol. 26, pp. 2408-2416, 2011.

[2] A. Zucker and T. Hinchliffe, "Optimum sizing of PV-attached electricity storage according to power market signals – A case study for Germany and Italy," *Applied Energy,* vol. 127, pp. 141-155, 8/15/ 2014.

[3] N. I. Nwulu and X. Xia, "Optimal dispatch for a microgrid incorporating renewables and demand response," *Renewable Energy,* vol. 101, pp. 16-28, 2 2017.

[4] G. Lorenzi and C. A. S. Silva, "Comparing demand response and battery storage to optimize self-consumption in PV systems," *Applied Energy,* vol. 180, pp. 524-535, 10/15/ 2016.

[5] P. Crespo Del Granado, Z. Pang, and S. W. Wallace, "Synergy of smart grids and hybrid distributed generation on the value of energy storage," *Applied Energy,* vol. 170, pp. 476-488, 5/15/ 2016.

[6] A. H. Mohsenian-Rad, V. W. S. Wong, J. Jatskevich, R. Schober, and A. Leon-Garcia, "Autonomous Demand-Side Management Based on Game-Theoretic Energy Consumption Scheduling for the Future Smart Grid," *Smart Grid, IEEE Transactions on,* vol. 1, pp. 320-331, 2010.

[7] I. Atzeni, L. G. Ordonez, G. Scutari, D. P. Palomar, and J. R. Fonollosa, "Demand-Side Management via Distributed Energy Generation and Storage Optimization," *Smart Grid, IEEE Transactions on,* vol. 4, pp. 866-876, 2013.

[8] Z. Wang, C. Gu, F. Li, P. Bale, and H. Sun, "Active Demand Response Using Shared Energy Storage for Household Energy Management," *Smart Grid, IEEE Transactions on,* vol. 4, pp. 1888-1897, 2013.

[9] R. A. Jabr, S. Karaki, and J. A. Korbane, "Robust Multi-Period OPF With Storage and Renewables," *Power Systems, IEEE Transactions on,* vol. 30, pp. 2790-2799, 2015.

[10] H. T. Haider, O. H. See, and W. Elmenreich, "A review of residential demand response of smart grid," *Renewable and Sustainable Energy Reviews,* vol. 59, pp. 166-178, 6 2016.

[11] X. Wang, C. Jiang, and B. Li, "Active robust optimization for wind integrated power system economic dispatch considering hourly demand response," *Renewable Energy,* vol. 97, pp. 798-808, 11 2016.

[12] C. A. Hill, M. C. Such, C. Dongmei, J. Gonzalez, and W. M. Grady, "Battery Energy Storage for Enabling Integration of Distributed Solar Power Generation," *Smart Grid, IEEE Transactions on,* vol. 3, pp. 850-857, 2012.

[13] Y. Wang, X. Lin, and M. Pedram, "A Near-Optimal Model-Based Control Algorithm for Households Equipped With Residential Photovoltaic Power Generation and Energy Storage Systems," *IEEE Transactions on Sustainable Energy,* vol. 7, pp. 77-86, 2016.

[14] H. O. R. Howlader, H. Matayoshi, and T. Senjyu, "Distributed generation integrated with thermal unit commitment considering demand response for energy storage optimization of smart grid," *Renewable Energy,* vol. 99, pp. 107-117, 12 2016.

[15] F. A. Chacra, P. Bastard, G. Fleury, and R. Clavreul, "Impact of energy storage costs on economical performance in a distribution substation," *Power Systems, IEEE Transactions on,* vol. 20, pp. 684-691, 2005.

[16] W. Lei, D. H. Liang, A. F. Crossland, P. C. Taylor, D. Jones, and N. S. Wade, "Coordination of Multiple Energy Storage Units in a Low-Voltage Distribution Network," *Smart Grid, IEEE Transactions on,* vol. 6, pp. 2906-2918, 2015.

[17] Z. Wang, F. Li, and Z. Li, "Active household energy storage management in distribution networks to facilitate demand side response," in *Power and Energy Society General Meeting, IEEE*, 2012, pp. 1-6.
[18] WesternPowerDistribution. (2011). *Buildings, Renewables and Integrated Storage, with Tariffs to Overcome network Limitations*. Available: http://www.smarternetworks.org/Files/B.R.I.S.T.O.L._130121172440.pdf
[19] WesternPowerDistribution. (2013). *SolaBristol Project*. Available: http://www.smarternetworks.org/Files/SoLa_Bristol_130802125955.pdf
[20] WesternPowerDistribution. (2013). *Project Sola Bristol*. Available: https://www.westernpowerinnovation.co.uk/Document-library/2013/PPR_WPD_SOLA_BRISTOL_MAY2013_PUBLIC.aspx
[21] WPD. (2014). *SoLa Bristol - ENA Smarter Networks Portal*. Available: http://www.smarternetworks.org/Project.aspx?ProjectID=394
[22] ELEXON. (2013). *Load Profiles and their use in Electricity Settlement*. Available: https://www.elexon.co.uk/wp-content/uploads/2013/11/load_profiles_v2.0_cgi.pdf
[23] Z. Wang, "Smart Pricing for Smart Grid," PhD, Electronic and Electrical Engineering, University of Bath, Doctor of Philosophy
[24] D. Altman, *Statistics with Confidence: Confidence Intervals and Statistical Guidelines*: British Medical Journal Books, 2000.
[25] B. M. Weedy, B. J. Cory, N. Jenkins, J. Ekanayake, and G. Strbac, *Electric power systems*: Wiley, 2012.
[26] IBM. (2015). *CPLEX Optimizer*. Available: http://www-01.ibm.com/software/commerce/optimization/cplex-optimizer/
[27] ENA. (2010). *Common Distribution Charging Methodology*. Available: http://www.energynetworks.org/electricity/regulation/structure-of-charges-cdcm/common-distribution-charging-methodology.html
[28] APX-ENDEX. (2015). *UK Power Market Result*. Available: http://www.apxendex.com/
[29] R. Li, Z. Wang, C. Gu, F. Li, and H. Wu, "A novel time-of-use tariff design based on Gaussian Mixture Model," *Applied Energy*, vol. 162, pp. 1530-1536, 1/15/ 2016.