Network pricing for customer-operated energy storage in distribution networks

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HIGHLIGHTS

- A novel charging and discharging method to minimise energy costs for customers.
- A new pricing scheme to reflect storage charging and discharging on systems.
- Cost-reflective tariffs for storage based on system investment & operation costs.
- Impact analysis of charging rate, storage capacity, and locations on pricing.

ABSTRACT

Network pricing is essential for electricity system operators to recover investment and operation costs from network users. Current pricing schemes are only for generation and demand that purely withdraws or injects power from/into the system. However, they cannot properly price energy storage (ES), which has the dual characteristics of injecting and withdrawing power. This paper develops a novel pricing scheme for ESs in distribution systems operated by customers to reflect their impact on network planning and operation. A novel charging and discharging methodology is designed for ESs to respond to time of use tariffs for maximising electricity cost savings. The long-term incremental cost for ES is designed based on future reinforcement horizon and short-term operation cost is quantified by system congestion. Then, a novel pricing scheme for ES is designed by integrating the two costs. The pricing signals can guide ES operation to benefit both distribution network operators and ES owners. The new methodology is demonstrated on a small system with an ES of different features and then on a practical Grid Supply Point (GSP) area.

1. Introduction

Energy storage (ES) plays a significant role in maintaining a resilient and robust electricity system by improving grid operating capability, lowering operation cost, and deferring/reducing network investments. In addition, because of the continuous growth of intermittent renewable energy, ES systems can improve system reliability and flexibility to accommodate more renewable energy, particularly wind and solar power [1,2]. For example, the current capacity of ES is less than 200 MW in the UK, which may increase to 1.6 GW by 2020 according to the forecast in [3].

A large volume of research has quantified the benefits from ES for different market players and designed various ES charging and discharging (C/D) strategies for various purposes. Papers [4–7] evaluate the costs and profits of ES, where the four main costs are: investment,

operation, maintenance, and energy purchasing. The savings are from network upgrade deferral and ancillary services [8–11]. Paper [5] discusses the social costs and benefits from wind-based energy storage are identified by determining financial incentives for energy storage. The benefits from arbitrage for energy storage is investigated in [6,7]. In these papers, ES is assumed to be owned by customers and responding to spot prices in the day-ahead. Based on real-time tariffs, paper [10] purposes a load shaping method to incentivise customers to store energy at low energy price periods so that the stored energy can be used during high price periods. Paper [12–15] discuss the C/D method for different storage technologies such as multi-tank thermal energy storage, lithium-ion storage, and gas-hydrate cool storage. The ES operation is investigated with tariff reward is discussed in Paper [15]. Paper [16,17] investigates the collaborative operation of ES and renewables. Paper [16] discusses the objective that to increase wind

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penetration. Paper [17] provides the market equilibrium interactions between ES and wind generators. But, these papers have not considering the economic impacts of ES to electricity networks.

There are still several barriers [18,19] obstructing the development and future penetration of ESs, which have been explored and emphasized by many academic and governmental reports [20–22]. Generally, in the order of perceived importance, the major barriers are:

- Network pricing
- Network connections
- Final consumption levies
- Planning Regulatory clarity

In terms of network pricing, it is the strategy to recover the investment cost and operation cost of networks from network users. The cost is allocated to all customers based on their contributions to network investment and congestion. Currently, two pricing methods are widely used on UK distribution networks: Long-run incremental cost (LRIC) [23] in extra-high voltage distribution networks and Distribution Reinforce Model (DRM) [24] in high voltage and low voltage distribution networks. However, they are only for traditional network users, generation and demand, which purely inject into or withdraw energy from networks strategies, but not applicable to ES considering its dual features (both importing and exporting energy). The development of technologies is far ahead of pricing method for ES [21]. The pricing for ES should be able to guide ES operation by setting appropriate price signals that reflect its impacts on networks. Thus, it is essential to develop appropriate pricing approaches that can be utilised by network operators to recover the network cost from ES.

The impacts on distribution networks from ES vary with C/D methods and ownership, which in turn affect network pricing for ES. There are three typical ES ownerships, customers, DNOs, and the third party [18,22,25]. If ES is owned by customers, it is normally used in responding to tariffs to reduce electricity bills or increase the bill saving resulting from ES operation. On the other hand, ES can also reduce use-of-system charges and congestion cost to improve network flexibility if appropriate ToU tariffs are designed. If ES is owned by DNOs, it can be used to benefit network infrastructures such as lowering line losses, minimising system operation costs, and reducing renewable curtailment and load disconnection. In papers [26–28], ES is utilised to mitigate network congestions by considering the charging control of electric vehicles. Papers [29–33] discuss C/D methodologies by setting different objectives, such as minimising line losses of distribution systems, minimising operation costs of electric vehicles, and reducing generation curtailment. Paper [32] uses ESs to manage power consumption of demand response. If ES is owned by the third party, it will be operated to respond to pricing signals of different purposes, such as ancillary services, retail market, to generate profits. However, these methods only analyse energy cost but ignore network costs that ES need to pay, thus not reflecting its impact on network investment.

This paper proposed a novel C/D strategy and pricing approach for customer-operated ESs. Customer-operated ES means that the storage installed in the households and operated by domestic customers, which should be operated to maximise the profits via electricity bill saving through energy price arbitrage. Firstly, the C/D method for ESs is developed in response to ToU tariffs, where Binary Search method (BSM) is utilised to adjust the state of charge (SoC) to maximise bill savings. Then, a pricing scheme for ESs is developed by using the core concept of LRIC, considering that: (i) network price signals should reflect the impacts of ES on future network reinforcement; (ii) the advantages of LRIC in generating locational forward signals. The new pricing method integrates system short-run congestion cost and long-run investment cost and then the impacts from ES on network investment and operation are converted into price signals. In short-term daily operation, the ES is operated to maximise the profits from energy arbitrage in response to ToU. This operation can actually help reduce system peak loading, if

operated during these periods, which reduces either investment or system congestion costs. In order to design more cost-reflective tariffs for ES, the savings from the reduction of investment cost and congestion cost should also be converted into pricing signals for ES. The long-term investment cost savings are allocated to the short-term operation periods by divide the savings to each period based on the mitigated congestion levels. In each period, the congestion and investment cost savings are combined together as new pricing signals to ES. The new tariffs can better incentive ES operation to help system operation. The impacts of different features of ESs on new system peak demand are also examined by sensitivity analysis which is demonstrated on a small system with various ES features. Then it is extrapolated to a real distribution system. Results illustrate its effectiveness in pricing ESs.

2. Importance of pricing for ES

ES is a key enabler to improve the balancing of generation and consumption, maximise the low carbon energy consumption and optimise the investment in infrastructure [34]. Although ES exists for many years, there are no pricing methods, especially for customer owned ESs, which normally sits behind the meter. Without appropriate pricing methods, there is a risk of competition distortion and a lack of level playing field for those using the network to deliver flexibility.

Currently, ES is treated as a non-intermittent generation in the UK system [19], but the guidance for charging method is an absence. In addition, the flexible connection of ESs cannot ensure their immediate actions, which means ESs are ignored in network pricing although it exports power at peak load times. As it 'consumes' energy and store it and then passes the energy to end consumers, the same electricity will be double counted from the payment of levies by both the storage providers and the consumers.

With the pricing method, an economic signal will be sent to ES if it can release network congestions and defer needed investment. Otherwise, it should be penalised if causing network problems, such as increasing system congestion.

The flowchart in Fig. 1 depicts the process of designing network pricing scheme, including two main steps.

- The first step is to design the C/D method for customer owned ES responding to ToU tariffs. The impacts of ES operation is reflected by the power flow change along network branches. The details are described in Section 3.
- In the second step, based on the contributions of ES to branch power flows, the investment cost and congestion cost of branches are calculated respectively for the with/without ES cases. Accordingly, pricing is designed based on the difference of network costs with and without ES operation. The details are given in Sections 4 and 5.

3. Models of charging and discharging methodology

ES is assumed to be controlled by customers in response to ToU tariffs to maximise profits (EP) from bill saving. The constraints are the power flow constraint, and node AC power flow constraint in (4), (5). Constraint (6) is the conservation of energy constraints of ES operation. The capacity balance between two dispatch intervals is in (4a), and the capacity constraints for discharging and charging are in (4b) and (4c)
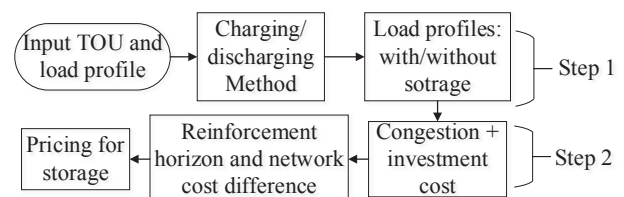

Fig. 1. Process of pricing for ES.